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GEOPHYSICS

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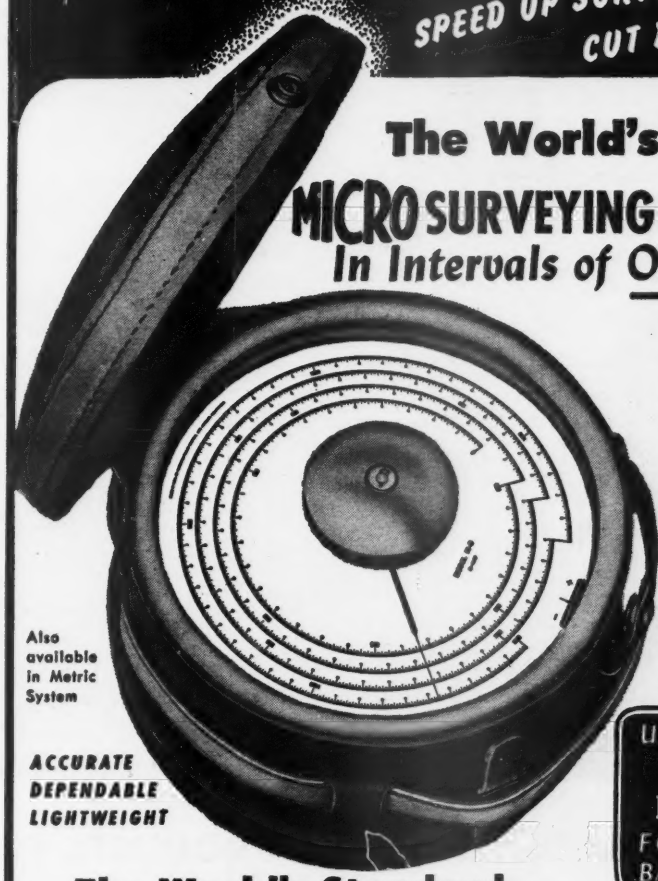

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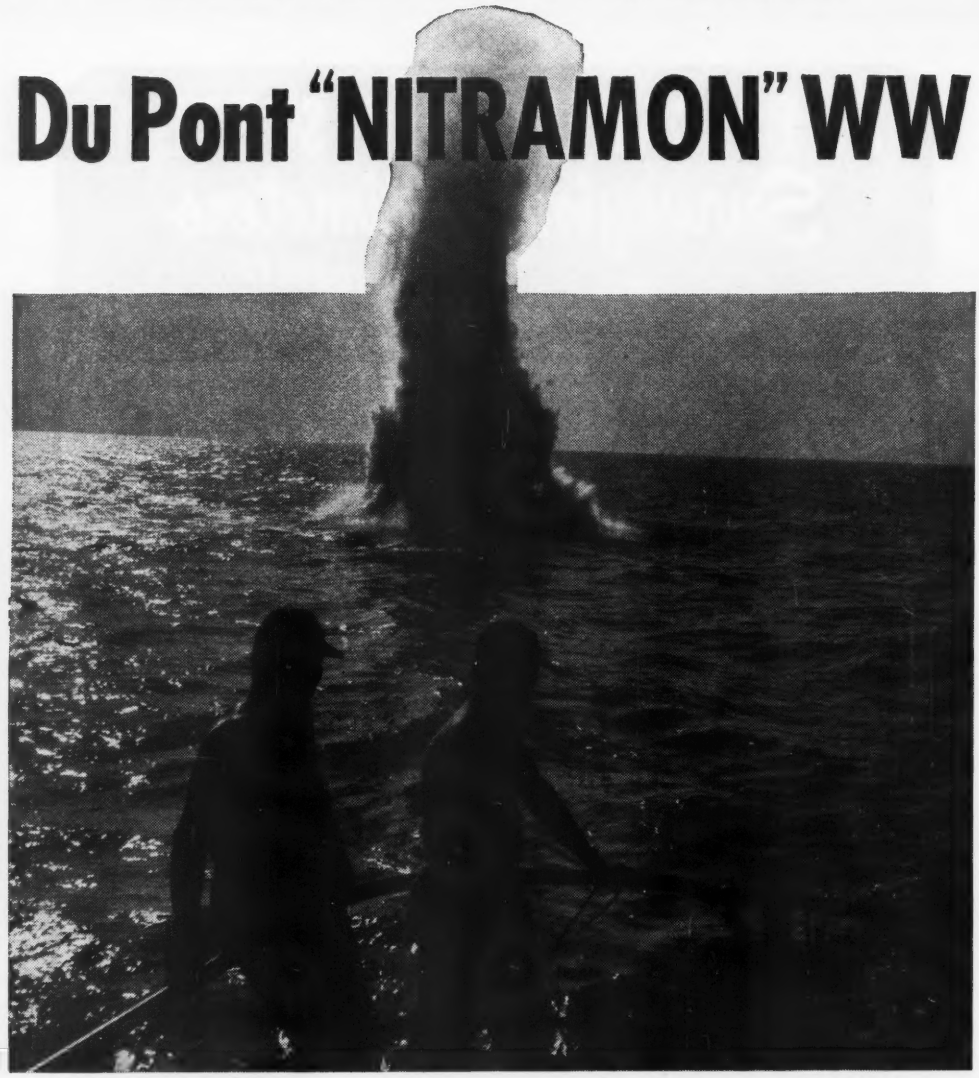

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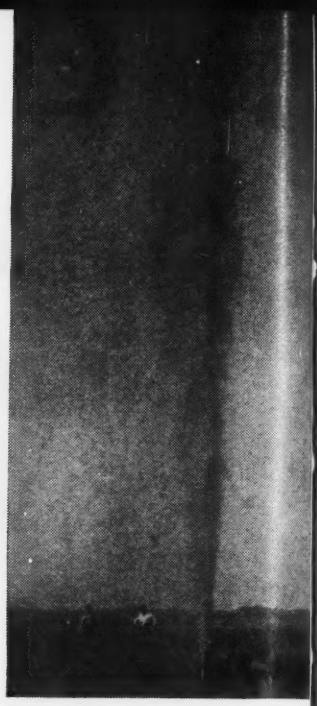

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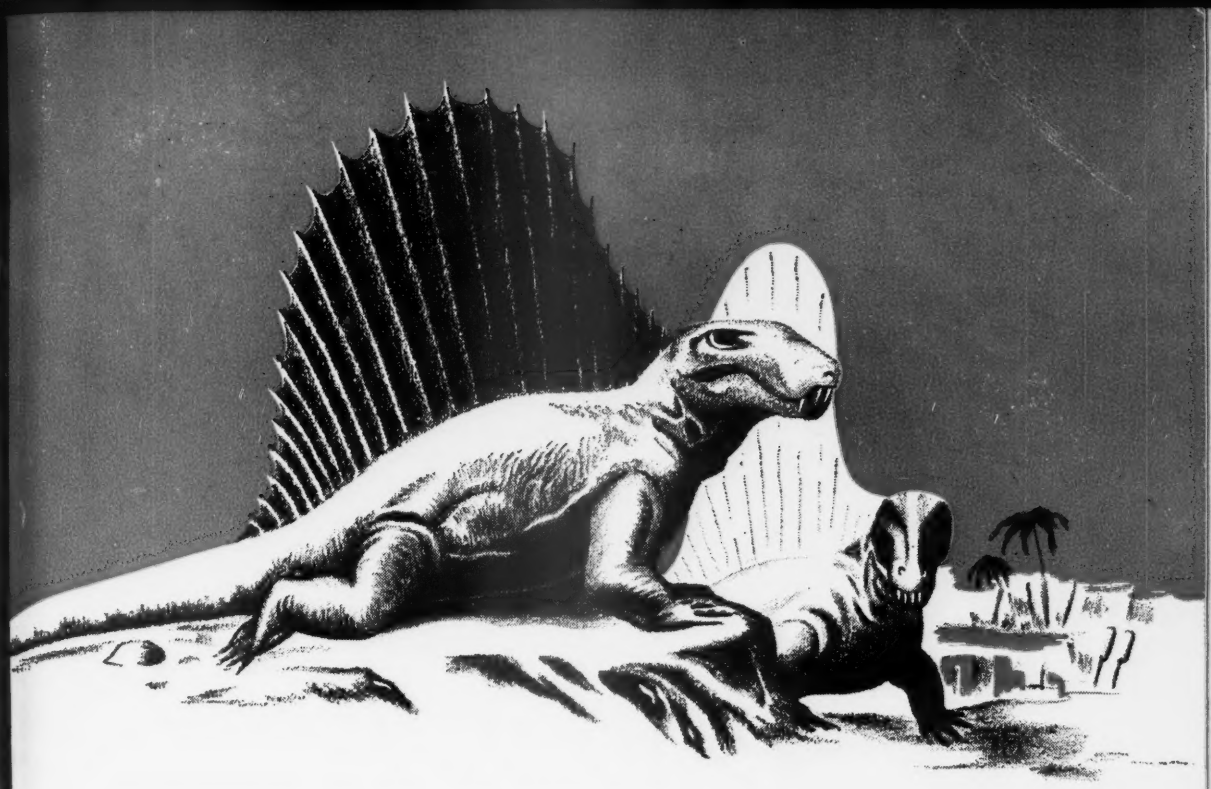

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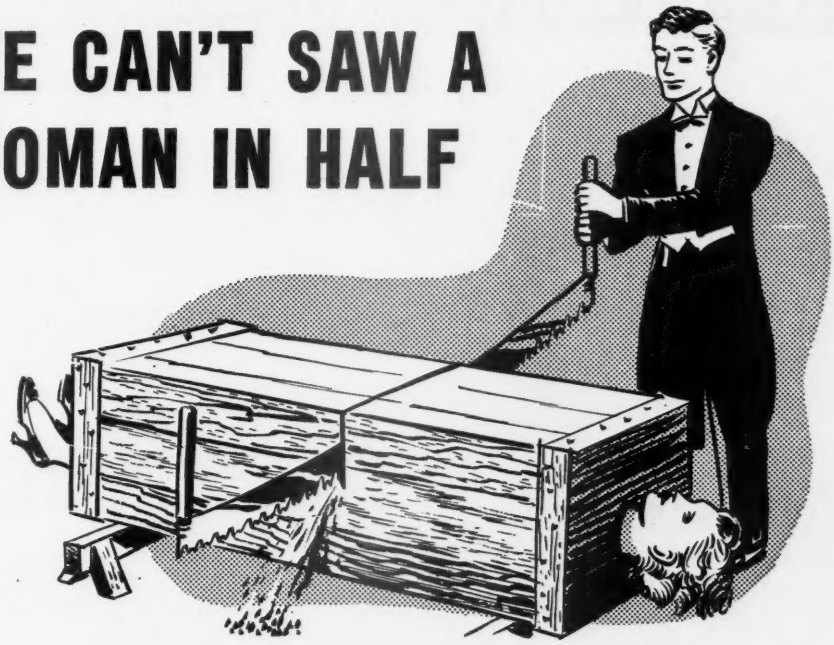

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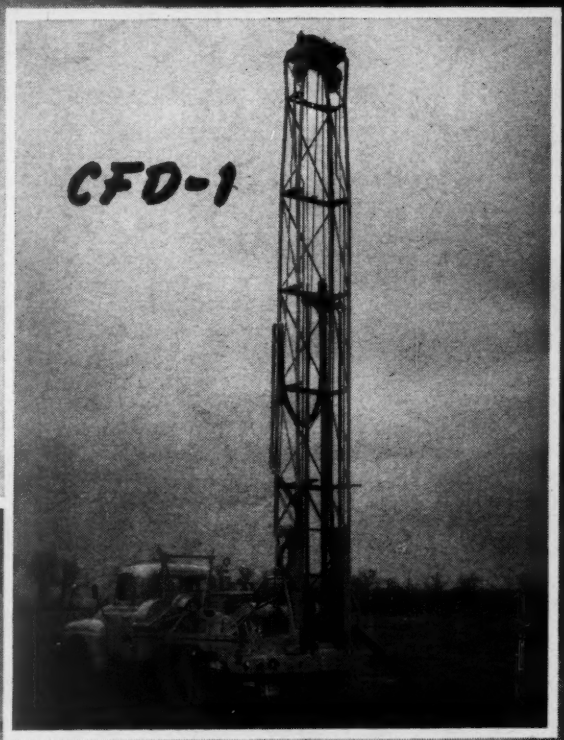

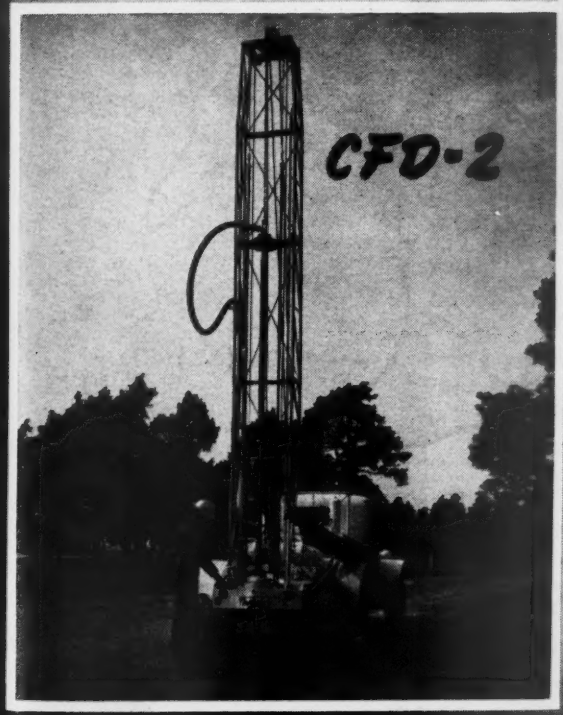

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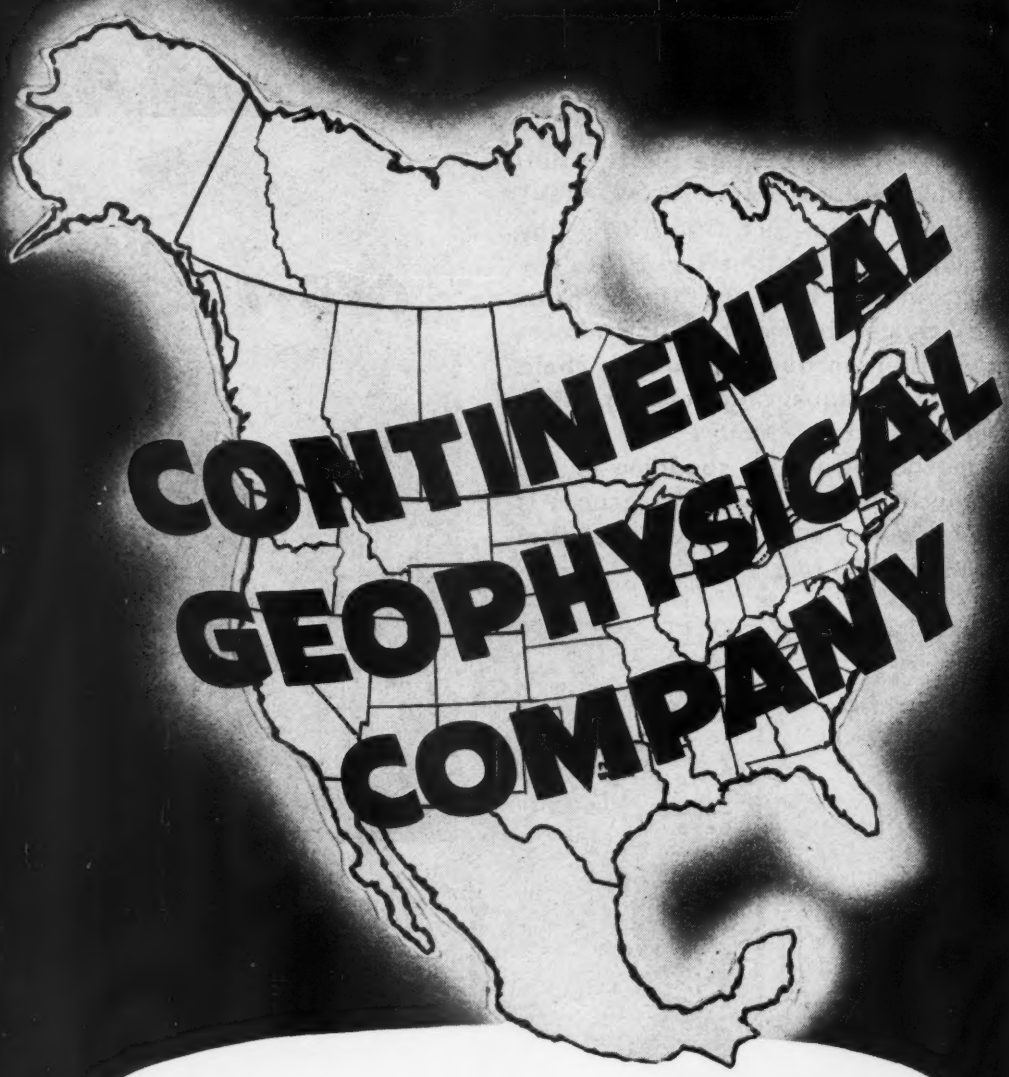

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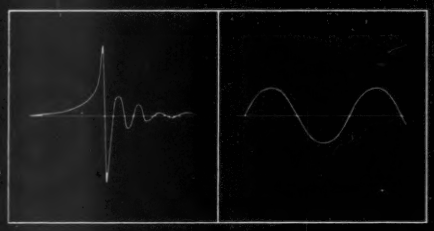

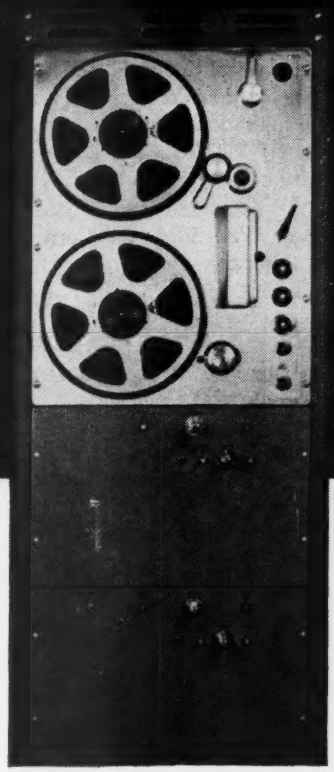

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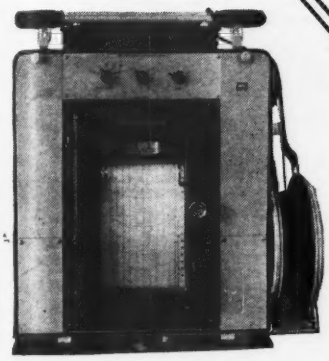

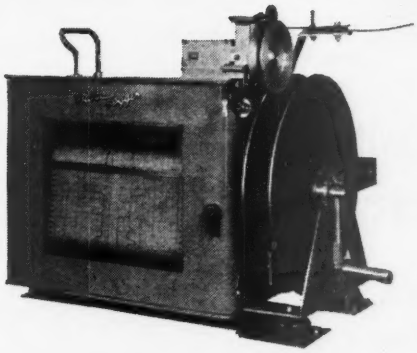

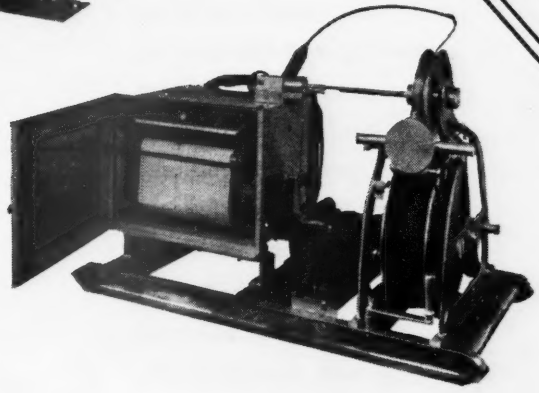

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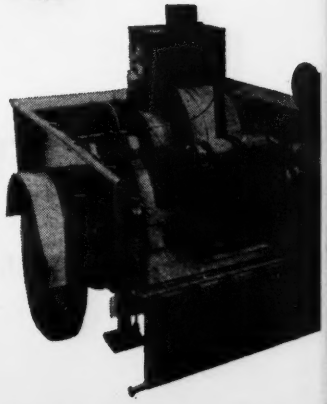

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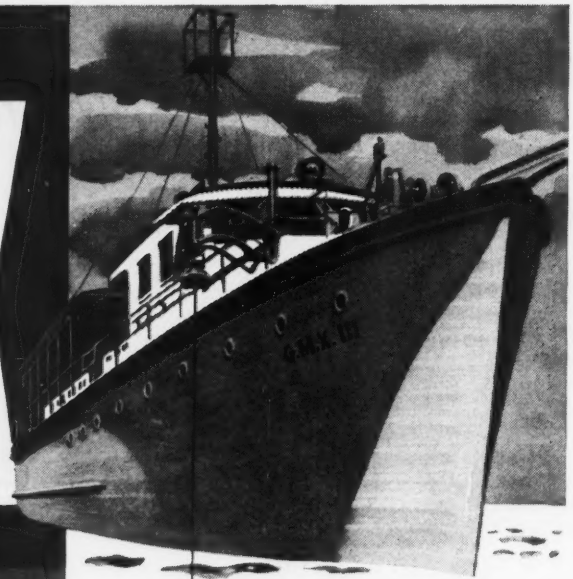

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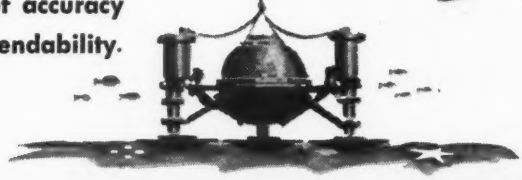

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A VELOCITY FUNCTION INCLUDING LITHOLOGIC VARIATION*

L. Y. FAUST†

ABSTRACT

Assuming velocity (V) a function of depth (Z), geologic time (T), and lithology (L) the resistivity log is an approach to the determination of L. Since general knowledge of water resistivity values (R_w) is lacking, the values of true resistivity (R_t) against $V/\alpha(ZT)^{1/6}$ were compared for 670,000 feet of section widely distributed geographically. Variations in R_w were presumably averaged out thereby, and the results indicate that statistically $L=[R_t]/T$ and $V=1948\ (ZTL)^{1/6}$. This formula was applied to an additional 270,000 feet of section more localized geographically to observe its accuracy in predicting vertical travel time. If a correction map for R_w variations is applied the results are encouraging but less accurate than good velocity surveys.

Examination of an inconclusively small amount of data with more careful measurements of R_t suggests that accuracy comparable to direct measurement may be attainable. The cooperation of other investigators and of the electric-logging specialists is desired.

INTRODUCTION

This paper describes an investigation of longitudinal seismic velocity in sedimentary rocks as a function of depth, geologic time, and lithology. A tentative lithologic parameter is designed utilizing data available from conventional resistivity logs. The variables are analyzed in nearly one million feet of section represented by one hundred and fifty velocity surveys. The goal of the investigation is the prediction of velocity from well logs with accuracy equal to direct measurement. While this accuracy has not been obtained, the results are encouraging. The latter portion of the paper examines the nature of the errors of prediction of the derived velocity function and suggests that the desired end may be attainable. A cooperative effort is proposed for the extension of the investigation.

A LITHOLOGIC PARAMETER

A previous paper[1] assumed that velocity v could be expressed as:

$$V = f(Z, T, L) \qquad (1)$$

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with Z the depth, T elapsed time since deposition, and L a lithologic variable. It was argued that by averaging many velocity measurements in essentially non-calcareous sections, the variable L was held constant and

$$V = \alpha(ZT)^{1/6}, \qquad L = L_1 \tag{2}$$

with L_1 representing "an average shale and sand section." The value of α was determined as 125.3 when Z was measured in feet, T in years, and V in feet per second.

In the previous paper evidence was presented that suggests a velocity formula including lithologic variation L would contain equation (2) as a member of a more generalized equation and that the variable L would appear either additively or as a coefficient of α. Since no generally accepted quantitative measure of lithologic variation L is available, a necessary first step is the formulation as a lithologic parameter of a quantity related to those lithologic variables which influence velocity. This quantity is found to be related to electric resistivity measurements. The following discussion will define first the factor in a velocity equation attributable to lithology. Next will be a description of the quantities influencing both this lithologic factor and resistivity. Then the steps necessary for the discovery of the desired lithologic parameter will be described in sequence.

The Lithologic Factor in a Velocity Equation

A Lithologic Factor K can be defined as:

$$K \equiv \frac{\Delta Z}{\Delta t} / \alpha(ZT)^{1/6} \tag{3}$$

where $\Delta Z/\Delta t$ is the actual measured velocity in the interval ΔZ and the denominator is the appropriate value for velocity from equation (2). Then $K=1$ for the lithologic conditions specified in equation (2) and in general K is that factor in velocity attributable to lithologic variation. It is therefore a quantity against which any tentative lithologic parameter can be tested. Previous to the definition of equation (3) an attempt was made to describe the effect of lithology on velocity as a term to be added to the right hand member of equation (2). The measurements to be described later were tested against that assumption with no correlative results.

The Resistivity Formation Factor

Archie has shown empirically that for permeable sections[2] the relation between true formation resistivity R_t and the resistivity R_w of the water impregnating the formation is given by

$$R_t/R_w = F = p^{-m} \tag{4}$$

where F is the "resistivity formation factor," p is proportional to porosity, and m is termed a "cementation factor." The number F derived from resistivity meas-

urements is unaffected by the mineralogical constituents of the formation matrix whose water-free resistivity approaches infinity but is a function of the porosity and cementation of the formation.

That the same quantities affect the factor K in velocity is well known. Some evidence on these facts can be found in the writer's previously cited paper and Vogel[3] mentions the inverse relationship of porosity and velocity when other variables are held constant.

There is reason therefore to anticipate that the desired lithologic parameter should be related to F, the resistivity formation factor of equation (4). Unfortunately while the values of R_t can be determined with some accuracy from Resistivity Departure Curves, the corresponding values of R_w are generally unknown. Wyllie[4] has indicated a solution for R_w for permeable formations, but this method does not apply to all sections.

In the absence of specific knowledge of R_w, if a sufficiently large number of measurements of R_t is averaged over a wide areal distribution, the corresponding averaged value of R_w should either remain constant under differing values of other variables or should vary in functional relationship to such variables. As a first step in this investigation it will be assumed that under such averaging the value of R_w remains constant. For ease of measurement it will be assumed that this constant value of R_w is unity. A quantity can then be defined

$$[R_t] \equiv \frac{1}{N}\sum^{N} R_t \Big/ \left(\frac{1}{N}\sum^{N} R_w = 1\right) \tag{5}$$

where N is the number of measurements and $[R_t]$, the magnitude of the average value of R_t, is dimensionless. Actually $[R_t]$ will be in a relationship to the average corresponding F value determined inversely by the relationship of $1/N\sum^{N}R_w$ to the variables to be studied, namely velocity, depth, geologic time, and lithology. Thus $[R_t]$ as defined in equation (5) is assumed to measure F or a quantity analogous to F.

Measurements

Measurements of R_t are derived from the value of R_a, the apparent resistivity, using bit size for the hole diameter correction and the appropriate value of mud resistivity, R_m, corrected for temperature. As a practical expedient some simplifications seem desirable. The values of R_a are taken, usually measured by the lateral device, over intervals (ΔZ) of approximately one thousand feet. The average value of R_a is taken from a smooth curve so drawn that the areas of positive difference between this curve and the measured trace are equal to the areas of negative difference. The extent of the segment of the curve is limited essentially by a maximum range of five to one in R_a variations. When larger variations occur the values of R_a and corresponding R_t are read over intervals less than one thousand feet and an average value of R_t determined for the desired interval. The

departure curves[5] used are those for beds of infinite thickness and no mud filtrate invasion.

While the inaccuracies introduced by these simplifications could not be tolerated by the petroleum engineer in the evaluation of thin oil bearing formations, simplified techniques still require a considerable amount of time and appear justifiable as a first approach to the problem.

Measurements of 670,000 feet of section corresponding to 96 velocity surveys have been taken from all available regions exclusive of Alberta and California. As wide lithologic variations as possible are included. The sections measured are, with minor exceptions, different from those reported previously. These data are then tabulated for value of geologic age T, depth interval ΔZ (usually one thousand feet), mean depth of burial Z, measured velocity $\Delta Z/\Delta t$, and the true formation resistivity R_t. Other quantities such as the appropriate velocity values from equation (2) and the value of K are derived and tabulated.

The Determination of a Lithologic Parameter

The obvious approach to the formulation of a tentative lithologic parameter involving $[R_t]$ is the study of the variation of $[R_t]$ when $K=1$. All data can be selected from the tabulated measurements where $K=1.00\pm0.10$. This specification is well within the limits of the data from which equation (2) was derived. The data corresponding to this restriction of K are then grouped by geologic time T. $[R_t]$ is determined from the data of each group. These results are plotted on logarithmic coordinates in Figure 1 and indicate that $[R_t]$ is nearly proportional to T. An attempt to split these data to investigate $[R_t]$ against Z for each value of T showed even poorer relationships but probably indicates that $[R_t]$ does not vary appreciably with depth. Although the relationship between $[R_t]$, Z, and T was not clearly determined, the assumption will be made and later verified that $[R_t]/T$ is independent of Z and T.

The quantity R_t/T, tabulated for all measurements, can be classified by value of T and subclassified for each T by the value of K in ranges of 0.10 from $K<0.90$ to $K>1.60$. The average K, the corresponding average $[R_t]/T$, and N, the number of measurements involved is summarized for each subclassification in Table I. Values involving less than ten measurements are considered unreliable and are not included. The data of Table I are plotted on logarithmic coordinates in Figure 2 and indicate a close approach to a linear relationship between the logarithms of K and of $[R_t]/T$. The values of $[R_t/]T$ show no tendency to deviate as a function of T. Figure 2 indicates that the required lithologic parameter L is defined by

$$L \equiv [R_t]/T. \tag{6}$$

A VELOCITY FUNCTION INCLUDING LITHOLOGY

The lithologic parameter L being determined, a velocity function including lithology can be formulated by comparison of L with K the lithologic factor. In

TABLE I. TABULATION OF DATA OF FIGURE 2

(Values of K, $[R_t]/T$ (reciprocal years) and number of measurements of thousand foot sections N arranged by values of Geologic Time T (years) and Lithologic Factor K.)

$10^{-6}T$		$< K < 0.90$	$\leqq K < 1.00$	$\leqq K < 1.10$	$\leqq K < 1.20$	$\leqq K < 1.30$	$\leqq K < 1.40$	$\leqq K < 1.50$	$\leqq K < 1.60$	$K \geqq 1.60$
26	K		0.96	1.02						
	$10^6[R_t]/T$		0.056	0.083						
	N		15	12						
43	K	0.87	0.94							
	$10^6[R_t]/T$	0.043	0.048							
	N	12	16							
70	K		0.95	1.04	1.14	1.23	1.37			
	$10^6[R_t]/T$		0.046	0.070	0.18	0.18	0.32			
	N		21	27	24	12	14			
192	K		0.97	1.04	1.15	1.24	1.35	1.44	1.55	1.71
	$10^6[R_t]/T$		0.089	0.113	0.19	0.19	0.41	0.55	0.78	1.32
	N		13	19	19	23	30	30	26	25
220	K		0.96	1.04	1.14	1.25	1.35			
	$10^6[R_t]/R$		0.064	0.072	0.240	0.560	0.490			
	N		44	53	22	15	15			
245	K					1.28				
	$10^6[R_t]/T$					0.375				
	N					11				

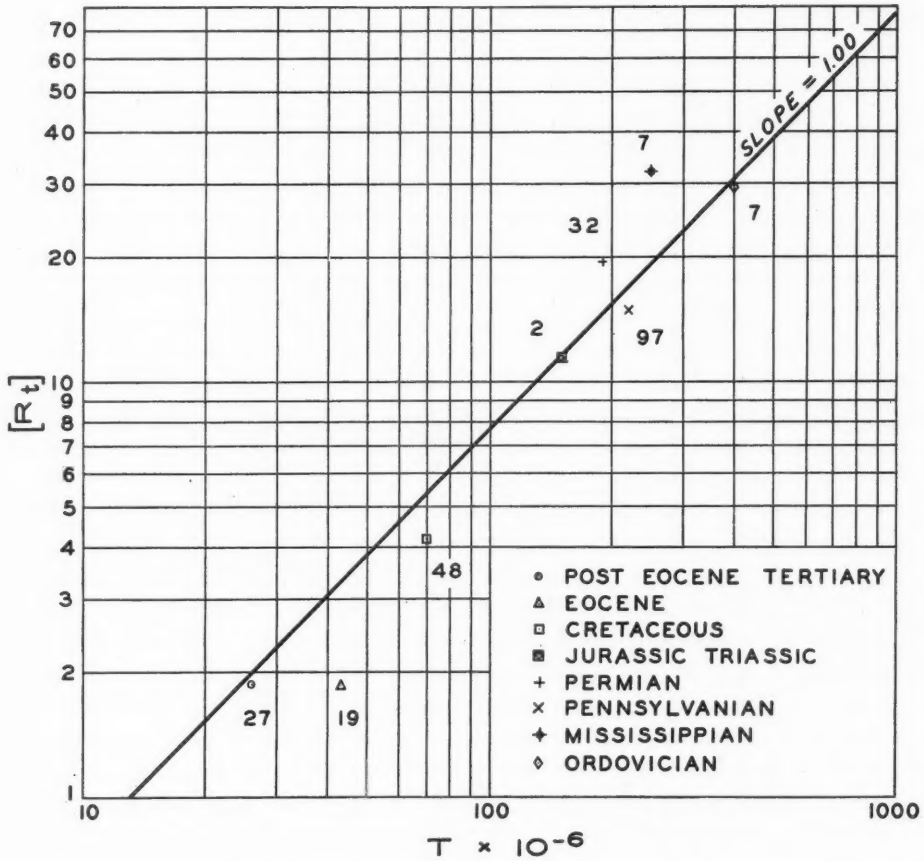

FIG. 1. $[R_t]$ as a function of geologic time T for an "average shale and sand section" ($K = 1.00 \pm 0.10$). The numbers above the plotted points show the number of thousand foot sections used in the determination. $[R_t]/T$ is nearly constant.

the following sub-sections will be shown first, the velocity formula and second, the predictability of this formula in individual wells. Due to the lack of knowledge of the individual values of R_w some error is to be expected. In the third part, an attempt will be made by analysis of additional data to show that the prediction errors are ascribable to variations of R_w and to suggest one method of correction.

The Velocity Formula

As a result of equation (6) all individual measurements of K can be grouped according to range of L regardless of age T. As a consequence one hundred and twenty measurements excluded from Table I could be included in these classifications. The average of L in each of five ranges together with the corresponding averages of K are plotted on logarithmic coordinates in Figure 3. These values

of $L \times 10^6$ and K are respectively: (0.048, 0.92), (0.075, 1.03), (0.183, 1.15), (0.487, 1.35), (1.03, 1.61). The number of measurements in each range is shown above each plotted point. A relationship of the form

$$K = CL^{1/n} \tag{7}$$

describes these points when $n = 6$. From equations (3) and (7) replacing $\Delta Z/\Delta t$ by V

$$V = \gamma(ZTL)^{1/6} \tag{8}$$

where

$$\gamma = 1948.$$

The type of averaging and classifying necessary to arrive at the results of Figure 3 should eliminate variations of R_w whether functional or random. This assumption is partly verified by the fact that Figure 2 confirms equation (7) although the method of grouping individual measurements was different. From equation (6) evidently

$$V = \gamma(Z[R_t])^{1/6}. \tag{9}$$

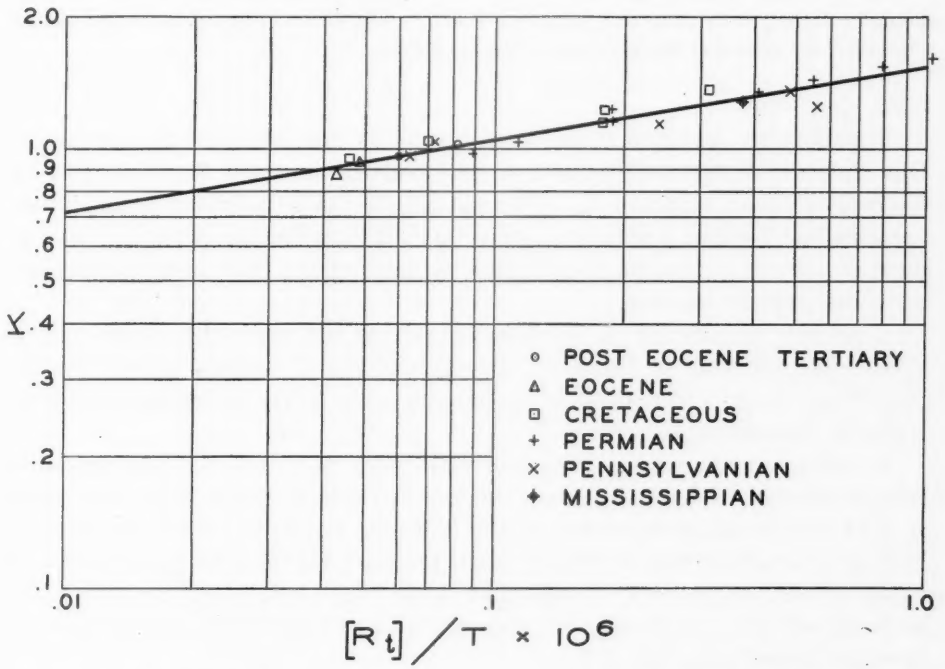

FIG. 2. The data of Table I plotted on logarithmic scale suggests that the lithologic factor K is proportional to $([R_t]/T)^{1/n}$ and that $[R_t]/T$ is independent of T.

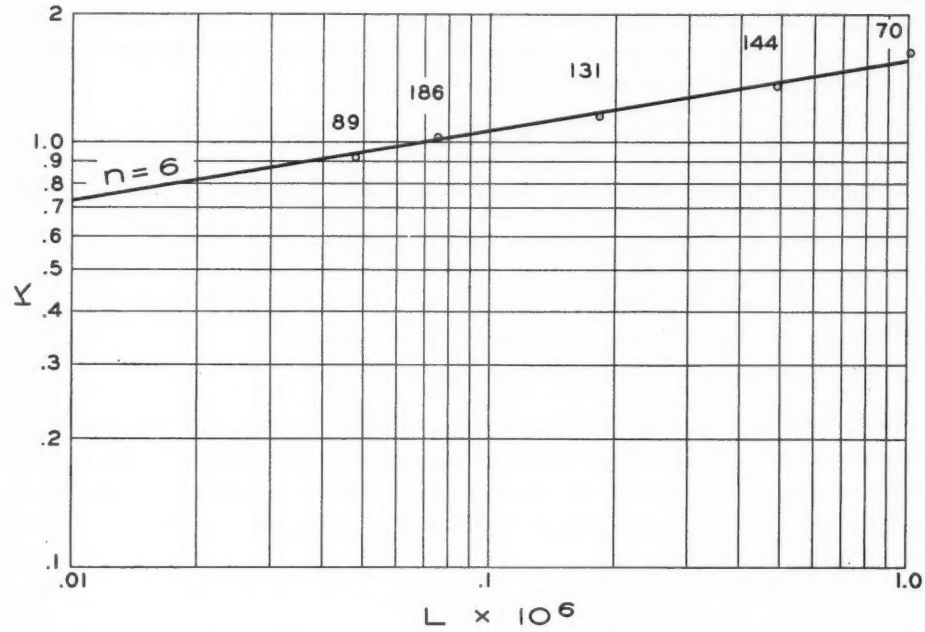

FIG. 3. Average values of the lithologic factor K versus the average value of the lithologic parameter L grouped by value of L show that $K=CL^{1/n}$ where $n=6$. Numbers above the plotted points show the number of thousand foot sections averaged.

Equation (9) describes statistically a velocity function including lithology. This equation represents the limit of the investigation until R_w values can be determined. Given values of R_w, L in equation (8) can be redefined to make that equation one form of a specific velocity law. Meanwhile the general utility of equations (8) or (9) can be investigated by determining their predictability for individual velocity surveys.

A possible implication of equation (9) is that the effect of geologic time T is lithologic. Heiland[6] in discussing the effect of age on velocity stated "An increased age merely increases the probability that it has undergone a greater degree of dynamometamorphism."

Possibly more surprising than the relationship of T and L is the apparent independence of $[R_t]$ and Z. This is checked in Table II where the average ratio of $\gamma(ZTL)^{1/6}$ to $\Delta Z/\Delta t$ is shown for the indicated number of measurements according to range of depth Z. There is some tendency for the ratio to increase with depth. In view of the present inadequate knowledge of R_w variations, this could be explained as a variation of R_w with depth or as evidence of an incompletely averaged lateral variation of R_w.

In defense of this latter supposition it should be pointed out that when equation (8) is tested in individual wells in the following discussion a correction

TABLE II. RATIO OF PREDICTED TO MEASURED VELOCITIES AGAINST DEPTH

(Average of indicated ratio for N observations classified by depth Z (feet). The slight increase with depth is not substantiated by other evidence.)

Z =	500	1,500	2,500	3,500	4,500	5,500	6,500	7,500	8,500	9,500	10,500	11,500
$\gamma(ZTL)^{1/6}/\frac{\Delta z}{\Delta t}$	0.947	0.970	0.928	0.929	0.933	0.983	1.009	1.018	1.017	1.047	1.099	1.073
N	16	38	54	60	61	55	46	38	29	21	12	8

in R_t for depth Z increases the errors of prediction. $[R_t]$ is considered therefore to be independent of Z.

Possibly the work of Gassmann[7] may be helpful in explaining the independence of the Z term.

Predictability

The data illustrated in Figures 2 and 3 are the average of measurements having a wide range of values. While the deviations could have been included in Tables I and II, the predictability of equation (8) should be a more useful measure of the errors. The evidence indicates that equation (8) represents a velocity law, but other variables not considered or a wide range of R_w values might produce such scattering of predicted versus measured velocities as to make equation (8) useless. When equation (8) or (9) is used to predict velocity in individual wells, the assumption of equation (5) of the constancy of R_w is no longer valid.

By a summation for each well of the time increments predicted by use of equation (8), the equality may be written:

$$\sum_{Z_1}^{Z_2} \frac{\Delta Z}{\gamma(ZTL)^{1/6}} = (t_2 - t_1) + \epsilon \tag{10}$$

where Z_1 and Z_2 are respectively the shallow and deep limits of available measurements in a well, t_1 and t_2 the corresponding measured vertical times, and ϵ the prediction error.

A group of fifty velocity surveys from the ninety-six used in the determination of equation (8) are analyzed in this manner with the results plotted on linear coordinates in Figure 4. The ordinate of each point is the value of the left hand member of equation (10) and the abscissa is the corresponding (t_2-t_1) value. The deviation from the Line of Correlation is the error ϵ. While the scattering is not too bad, one measured time (t_2-t_1) at 0.588 seconds has an ϵ of -0.090 second. The greatest positive value of ϵ is 0.054 second and the mean value of $|\epsilon|$ is 0.026 second.

If ϵ is a function of ΔR_w, a total variation in this function of five to one is sufficient to reduce ϵ to zero for the extreme deviations. Available measurements[8] of R_w show variations of greater than one hundred to one. Since these latter are observed in permeable sections, the water resistivities measured are not necessarily of water laid down with the formation. On occasion the water present in a permeable formation may be meteroic. Nevertheless the range of five to one necessary to explain these ϵ's is conceivable.

If the prediction errors may be explained as the effect of variations in R_w, then

$$V = \gamma'(Z\Phi)^{1/6} \tag{11}$$

may be the final form of a law governing velocity where Φ is proportional to R_t and is a function of R_w. Φ is analogous to or equal to F.

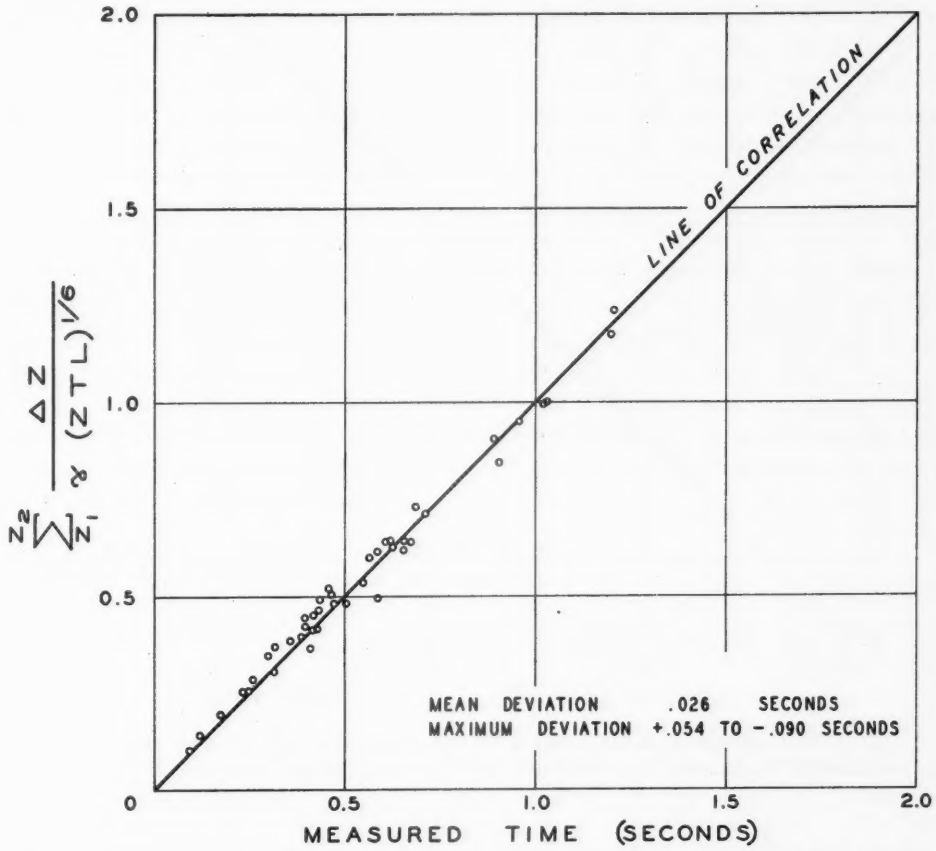

FIG. 4. Scattering of predicted one way travel times versus measured travel times for fifty wells taken over a wide geographical distribution. The deviations could be explained by a 5 to 1 range in the effect of R_w.

The Variation of Water Resistivity

The validity of the assumption upon which equation (11) is suggested may be verified in part by other indirect evidence. The values of ϵ shown in Figure (4) are from data taken over a wide geographical distribution with consequent variations in depositional environment. If sufficient data were available in a more localized area, the range of R_w variation should be more restricted. Such a condition exists in Alberta where forty-six velocity surveys not used in the development of equation (8) represent 270,000 feet of additional section. All of these surveys include measurements of some Paleozoic section as well as younger formations. If the range of ϵ's for this group of surveys were considerably less than those of Figure 4, the argument that $\epsilon = f(\Delta R_w)$ would be sustained in part.

The short time span over which the Alberta wells were drilled insures that

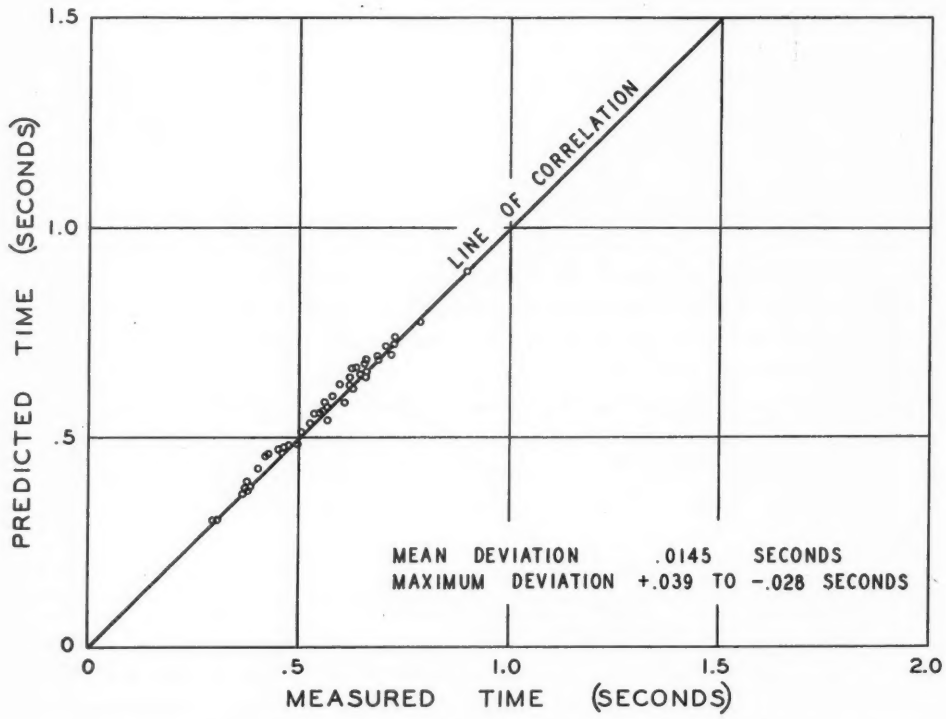

FIG. 5. A comparison similar to Figure 4 for forty-six Alberta wells not used in the derivation of equation (8). Variations of R_w should be less in this more restricted area and the deviations are smaller.

all the electric logs used in this study represent a single phase of development. The Alberta surveys show a deviation from equation (2), ($K=1$) from $+0.075$ seconds to -0.186 second with twelve of the surveys having deviations of a few milliseconds from that formula. The area is therefore useful also in evaluating the properties of L.

The results of the application of equation (9) to the forty-six Alberta surveys are plotted on linear coordinates in Figure 5 and show ϵ values ranging from $+0.039$ to -0.028 second with a mean $|\epsilon|$ of 0.0145 second. While tending to confirm the assumption that $\epsilon=f(\Delta R_w)$, the range of the ϵ's is unsatisfactorily large since it is assumed that good direct measurements have an accuracy of five milliseconds.

The distribution of the forty-six surveys in Alberta is shown in Figure 6. Although restricted to one general basin the dimensions of the area are approximately seven hundred by two hundred miles. Some variation of R_w may be expected over that extent. A rough measure of the assumed effect of R_w variation can be determined by indicating $\Delta\epsilon/\Delta Z$ for each well. The signed numbers in Figure 6 show this measure in milliseconds per thousand feet. Generalized

contours of these quantities are shown. Although possibly fortuitous, the shape of the contours is similar to that of the epicontinental seas receding in this area through Mesozoic time. The easternmost well shown in Figure 6 and a well (not shown) off the south edge of the map were used for contour control only and are not included in the analysis. The data of Figure 5 are corrected by interpolation of the contours of Figure 6 except that all values within the $+5$ contour are taken as $+5$. The results are shown in Figure 7. The mean $|\epsilon|$ is 0.0079 second with a range of ϵ's from $+0.020$ to -0.018 second.

The wells indicated as *A* through *F* in Figure 6 are shown in cross section in Figure 8 where the uncorrected ϵ's are indicated by circles connected by dashed lines and the ϵ's corrected by Figure 6 are indicated by asterisks connected by solid lines. Three of the wells, namely *A*, *C*, and *F*, have corrected ϵ's of five milliseconds or less while the other three wells have the maximum variations of Figure 7. Evidently no generalized recontouring of Figure 6 would improve materially these errors, and therefore the errors shown in Figure 7 represent the limitation of the correction for R_w.

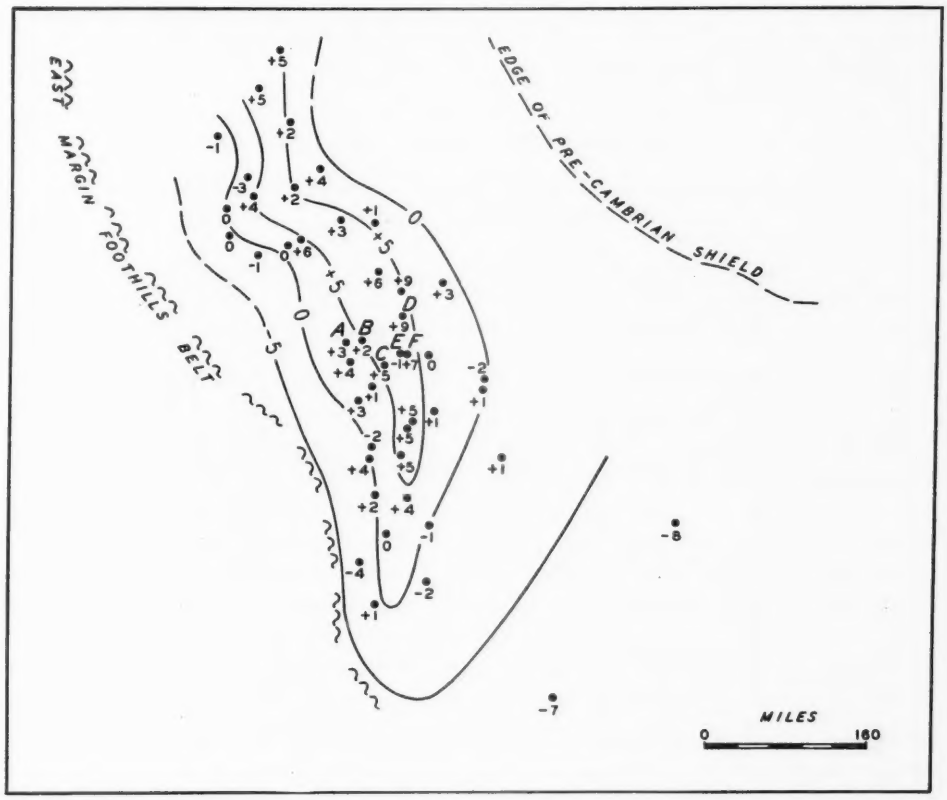

FIG. 6. Generalized contours of the deviations per thousand feet of the wells of Figure 5.

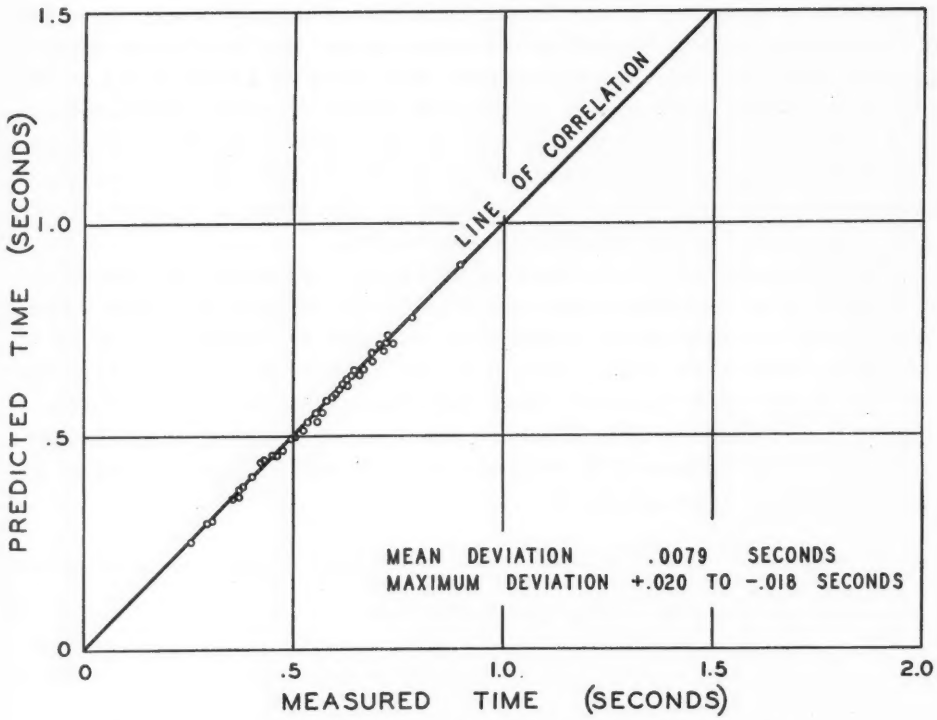

FIG. 7. A comparison for the same wells as shown in Figure 5 corrected by the contoured values of Figure 6.

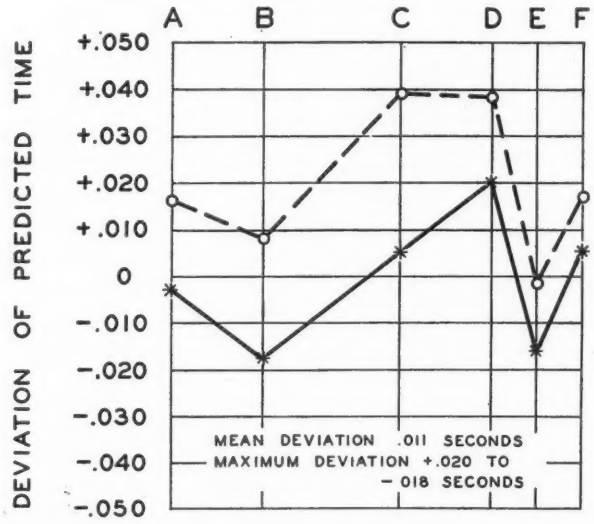

FIG. 8. A cross section of the wells indicated A-F of Figure 6 showing the uncorrected deviations (dashed lines) and the corrected deviations (solid lines). The variations between adjacent wells show that the limit of correction for R_w has been reached.

Since the method of determining R_t as discussed previously involved the introduction of some error, a more careful measurement should reduce the errors if equation (8) were exact when corrected for R_w but would have at least equal probability of resulting in larger ϵ's if the law were approximate only. The data of the six surveys of Figure 8 are re-evaluated by consideration of bed thickness, mud filtrate invasion, and the use of one hundred foot or smaller intervals of measurement. The revised data are shown in Figure 9. Although there is no improvement in the uncorrected values, the corrected ϵ's vary from $+0.008$ to -0.007 second with a mean $|\epsilon|$ of 0.005 second. Two other wells originally

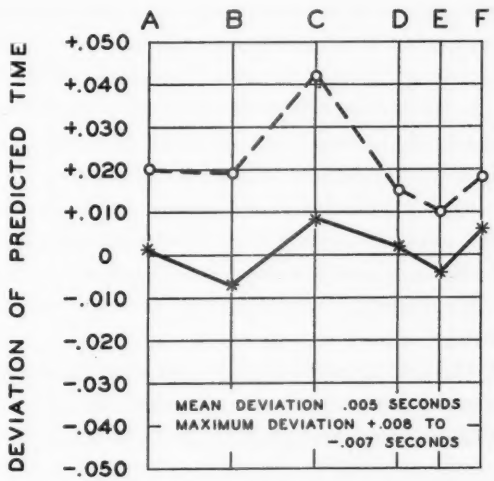

FIG. 9. The same wells as in Figure 8 showing the deviations when R_t is determined with greater accuracy. These corrected deviations are comparable in accuracy to direct measurement.

showing corrected ϵ values of -0.016 and -0.017 respectively have ϵ's of plus four and plus one milliseconds by the more accurate measurements.

It would be absurd to imply that the small errors in these eight wells are a real measure of the achievements of this study since the accumulation of more data will almost certainly disclose some large departures.

It is recognized that the arguments relating the prediction errors to variation of R_w do not prove conclusively that this is the correct explanation. Other possibilities have not been excluded. It is demonstrated however that the prediction errors are essentially systematic rather than random.

This paper has described the results of all but six surveys which have been used in testing equation (8). These six surveys represent a more recent effort by the writer to test the equation against the most anomalous velocity conditions. All six have checked satisfactorily. The most anomalous of this group is a deep survey in the Gulf Coast called to the writer's attention by O. B. Manes. This survey has a measured vertical time in excess of the predicted time from equation

(2) by nearly three-tenths of a second. Equation (8) predicts the measured time to twenty-one milliseconds (uncorrected).

Evaluation of Results

It is believed that equation (8) or its equivalent, equation (9), may be regarded as a statistical law governing velocity. While the improvement in prediction accuracy with each refinement is evidence favoring the conclusion that acceptable accuracy may be attainable, the results of the study of the Alberta velocities should not be generalized without further confirmation.

Since the measured vertical time over the greatest possible depth range represents usually the most accurate measurement of a conventional velocity survey, the predictions of equation (8) have been referred only to such measurements. It is arguable that in some shorter interval the predicted velocities could be the more accurate. K. S. Cressman under the general supervision of the writer has been successful apparently in using equation (8) in short intervals in a study of the composite nature of reflections. However resistivity measurements across small intervals of varying resistivity are inexact. While Summers and Broding reported a generally good correspondence[9] between five foot interval velocity logs and resistivity, Broding has stated in his discussion of the first presentation of this paper[10] that in some wells a total lack of correspondence has been observed over certain intervals.

The problem of the formulation of Φ in equation (11) requires consideration not only of the errors of the velocity formula but also of those errors involved in direct velocity measurement and especially of the errors in resistivity measurement.

The writer is not qualified to discuss the significance of this study from the viewpoint of the resistivity specialist. The work of Owen in emphasizing the importance of cementation[11] on resistivity may have an important bearing on this problem.

A CO-OPERATIVE INVESTIGATION

Two approaches to the practical use of these relationships seem possible. The preparation of correction maps with present techniques could be instituted immediately. The improvements in resistivity measurements and techniques for determining R_w variations await future development.

The Use of the Present Techniques

Much more investigation will be required before the general accuracy of these empirically derived formulae is ascertained. Independent work in this field is desirable. One suggested project is an attempt to duplicate Stulken's[12] velocity maps in the Bakersfield region by means of electric logs. It should he mentioned however that the re-evaluation of the data shown in Figure 9 required the equivalent of one work week. It may be preferable therefore to institute further investi-

gation on a cooperative basis. The confidential nature of most velocity information might seem to bar such a venture. The writer has available a library of more than one thousand velocity surveys and would be willing to serve as a clearing house in the dissemination of non-confidential material. Correspondence could be confined to surveys available both to the writer and to the particular investigator. Maps of the areas of interest could be prepared similar to that shown in Figure 6. It is evident that such a correction map should be made within each general unconformity. These correction maps, being non-confidential, could be distributed to all collaborators. A first requirement would be an argeement on a standard method of measuring R_t determined preferably with the advice of specialists in electric logging.

Improvement of the Method

Improvements in the method depend primarily on the electric logging specialists and service companies. It would be helpful to show the zero deflection at both the start and end of a run. The deflection corresponding to one standard resistivity would be desirable. The example in Figure 4 of $\epsilon = -0.090$ is suspected of being an error in scale since the readings were abnormally high for all depths. Lacking good evidence on this point however the value was included. The clarification of the multiple scale traces would be useful. In Gulf Coast areas of low resistivity, a complete set of amplified curves would improve accuracy.

The newer logging devices may be expected to improve accuracy, especially in West Texas. However a measurement of R_w for the complete section is of paramount importance. Offers of aid in such a project have been received. Dr. Leendert de Witte has suggested[13] an extension of Wyllie's method for correcting for R_w to a first approximation. It is hoped that it will now be possible for the writer to secure the collaboration of an electric log specialist in comparing the results of this suggested correction with the data of Figure 6.

ACKNOWLEDGMENTS

Appreciation is expressed to Dr. B. B. Weatherby for permission to publish this paper. The writer is indebted to E. E. Finklea for information concerning resistivity measurements, to F. F. Campbell for his valuable aid in the writing of this paper and especially to K. M. Lawrence and Paul Lyons for their encouragement. The figures were prepared by the Amerada Drafting Department.

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VELOCITY FUNCTIONS IN SEISMIC PROSPECTING*

H. KAUFMAN†

ABSTRACT

An account of the mathematical properties of velocity functions used in the seismic method of geophysical prospecting is presented. Basic equations are given for deriving various quantities of interest associated with a particular velocity function, such as average velocity as a function of depth, average velocity as a function of vertical travel time, parametric equations for displacement, depth, travel time, etc. In Part I the relations are based on a given instantaneous-velocity—depth function. Part II contains a similar analysis based on a given instantaneous-velocity—vertical-time function. The results are incorporated in Tables I and II.

INTRODUCTION

The computation of depths and displacements in the seismic method of geophysical exploration requires an accurate knowledge of the velocity variations in the region under consideration. To keep the mathematical treatment reasonably simple the assumption is usually made that the velocity is a function of depth only. The case receiving most attention is that for which the instantaneous velocity is a linear function of depth. Less complete treatments have been given for the parabolic and exponential functions.

The velocity can also be considered as a function of vertical travel time. Since there is a unique correspondence between depth and vertical time, the two methods of representation are essentially equivalent; however, certain types of velocity—vertical-time functions may be simpler to study than the corresponding types of velocity-depth functions. The relative advantages have been discussed by Mott-Smith (1, 2).

Muskat (3) has considered the case where the depth is given explicitly in terms of instantaneous velocity. This method is of value in those cases where it is extremely difficult, if not impossible, to find the velocity explicitly in terms of depth.

A survey of the literature shows that, despite a rather large number of articles on particular functions, a unified treatment is not available. The chief object of the present paper is to give an account of the properties of velocity-depth and velocity—vertical-time functions, the results being incorporated in Tables I and II. The selection of specific functions has been guided by those receiving some mention in the geophysical literature. The analysis of any new proposed function can be systematically carried out by the procedures developed here.

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NOTATION

z	depth to any point on ray-path
t_v	vertical travel time (one-way) to any point on ray-path
t	travel time along ray-path to any point on ray-path
x	displacement (horizontal distance) from shot-point to any point on ray-path
Z	maximum depth of penetration
T	surface-to-surface travel time
X	range; i.e., displacement from shot-point to point of emergence of completely refracted ray
$v(z)$	instantaneous velocity as a function of depth
$v(t_v)$	instantaneous velocity as a function of vertical travel time
$v_a(z)$	average velocity as function of depth
$v_a(t_v)$	average velocity as a function of vertical travel time
θ	angle between ray-path and vertical at any point of path
θ_0	value of θ at shot-point (also equal to emergence angle)
p	constant for ray-path, $p=\sin\theta/v=\sin\theta_0/v_0$
$\Gamma(n)$	Gamma function
$F(\phi, k)$	incomplete elliptic integral of first kind of modulus k
$E(\phi, k)$	incomplete elliptic integral of second kind of modulus k
$F(\pi/2, k)=K(k)$	complete elliptic integral of first kind
$E(\pi/2, k)$	complete elliptic integral of second kind

PART I

Relations based on a given instantaneous-velocity—depth function

Referring to Figure 1, let Ox and Oz be the horizontal and vertical axes respectively, where O represents the shot-point. Let θ be the angle between the ray-path and the vertical at any point of the path, and θ_0 the emergence angle. The displacement, x, and travel time, t, are given by:

$$x = \int_{\theta_0}^{\theta} \frac{\sin\theta d\theta}{pv'(z)}, \tag{1.1}$$

$$t = \int_{\theta_0}^{\theta} \frac{d\theta}{v'(z)\sin\theta}, \tag{1.2}$$

which constitute the parametric equations for x and t in terms of θ as parameter. Note that $v'(z)\equiv dv/dz$ must be expressed as a function of θ before the integrations can be performed.

The parametric equation for the depth

$$z = z(\theta) \tag{1.3}$$

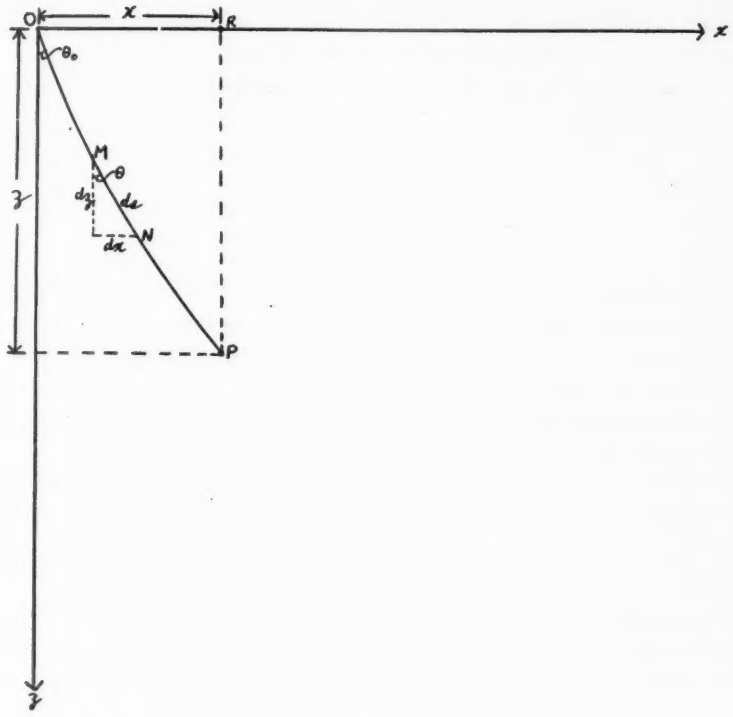

FIG. 1

is obtained from the given velocity-depth function together with the relation $pv = \sin\theta$.

The parametric equations of the ray-path are given by (1.1) and (1.3).

The range, X, surface-to-surface travel time, T, and maximum depth of penetration, Z, are given by:

$$X = 2\int_{\theta_0}^{\pi/2} \frac{\sin\theta d\theta}{pv'(z)}, \tag{1.4}$$

$$T = 2\int_{\theta_0}^{\pi/2} \frac{d\theta}{v'(z)\sin\theta}, \tag{1.5}$$

$$Z = z(\pi/2). \tag{1.6}$$

The relation between depth and vertical travel time is

$$t_v = \int_0^z \frac{dz}{v(z)} \tag{1.7}$$

which defines t_v in terms of z. In relatively simple cases it is then possible to solve for z in terms of t_v, but this will not generally be true.

The average velocity, v_a, to any depth is defined as the ratio of depth to vertical time. By (1.7)

$$v_a(z) = \frac{z}{\int_0^z \frac{dz}{v(z)}}. \tag{1.8}$$

The instantaneous-velocity—vertical-time function corresponding to the given instantaneous-velocity—depth function is obtained by eliminating z from the equations $v=v(z)$ and $t_v=t_v(z)$ to yield the desired relation $v=v(t_v)$. In many cases it may not be possible to eliminate z because of analytical difficulties; however the pair of equations $v=v(z)$ and $t_v=t_v(z)$ should still be considered as parametric equations relating v and t_v in terms of z as parameter.

Similarly the corresponding average-velocity—vertical-time function is obtained by eliminating z from equations (1.7) and (1.8). Again, if z cannot be eliminated the two equations still constitute a parametric representation for the v_a-t_v relation in terms of z as parameter.

The above analysis provides the basis for the computation of Table I. Blank entries in the table indicate lack of a corresponding explicit formulation. We append here some notes and discussion which could not be incorporated in the table.

(a) $v=v_0(1+kz)^{1/n}$. This function is of sufficient generality to cover a number of cases of practical importance; thus $n=1$ and $n=2$ yield immediately the linear and parabolic functions respectively. The similarity of functional form for $n\neq 1$, of the velocity-depth and corresponding velocity—vertical-time functions should be noted. In particular the parabolic velocity-depth function corresponds to the linear velocity—vertical-time function.

With a slight rearrangement of constants the function can be written in the form $v=\alpha(z+A)^{1/n}$, which has been used by Banta (4) in an application to weathering problems.

(b) $v=v_0(1+kz)$. The velocity is a linear function of depth. This is a special case of (a) with $n=1$, and is the one most commonly treated in the literature.

Ray-path. Using Table I the parametric equations of the ray-path can be written as

$$x - \frac{\cot\theta_0}{k} = -\frac{1}{k\sin\theta_0}\cos\theta,$$

$$z + \frac{1}{k} = \frac{1}{k\sin\theta_0}\sin\theta,$$

which are the parametric equations of a circle of radius $1/(k\sin\theta_0)$ with center at $x=\cot\theta_0/k$, $z=-1/k$. It follows that the ray-path circles all have their centers

Instantaneous-Velocity—Depth Function	Corresponding Average-Velocity—Depth Function	Corresponding Instantaneous-Velocity—Vertical-Time Function	Corresponding Average-Velocity—Vertical-Time Function
$v=v(z)$	$v_a=v_a(z)$	$v(t_v)$	$v_a=v_a(t_v)$
$v_0(1+kz)^{1/n}$	$\dfrac{(n-1)kv_0}{n}\cdot\dfrac{z}{(1+kz)^{(n-1)/n}-1}$ $n\neq 1$	$v_0\left[1+\dfrac{(n-1)kv_0}{n}\,t_v\right]^{1/(n-1)}$ $n\neq 1$	$\dfrac{\left[\left(1+\dfrac{(n-1)kv_0}{n}\cdot t_v\right)^{n/(n-1)}-1\right]}{kt_v}$ $n\neq 1$
$v_0(1+kz)$	$\dfrac{kv_0z}{\log(1+kz)}$	$v_0e^{kv_0t_v}$	$\dfrac{e^{kv_0t_v}-1}{kt_v}$
$v_0(1+kz)^{1/2}$	$\dfrac{v_0}{2}\left[(1+kz)^{1/2}+1\right]$	$v_0(1+\frac{1}{2}kv_0t_v)$	$v_0(1+\frac{1}{4}kv_0t_v)$
$v_0(1+kz)^{1/3}$	$\dfrac{2kv_0z}{3\left[(1+kz)^{2/3}-1\right]}$	$v_0(1+\frac{3}{2}kv_0t_v)^{1/2}$	$\dfrac{\left[(1+\frac{3}{2}kv_0t_v)^{3/2}-1\right]}{kt_v}$
$v_0+Az^{1/n}$	$\dfrac{A^nz}{n\displaystyle\int_{v_0}^{v}\dfrac{(v-v_0)^{n-1}}{v}\,dv}$	$t_v=\dfrac{n}{A^n}\displaystyle\int_{v_0}^{v}\dfrac{(v-v_0)^{n-1}}{v}\,dv$	
$v_0+Az^{1/2}$	$\dfrac{A^2z}{2\left[Az^{1/2}-v_0\log\left(1+\dfrac{Az^{1/2}}{v_0}\right)\right]}$	$t_v=\dfrac{2}{A^2}\left[v-v_0-v_0\log\dfrac{v}{v_0}\right]$	
$Az^{1/n}$	$\dfrac{(n-1)}{n}Az^{1/n}$	$\left(\dfrac{n-1}{n}\cdot A^n\right)^{1/(n-1)}t_v^{1/(n-1)}$	$\left(\dfrac{(n-1)A}{n}\right)^{n/(n-1)}t_v^{1/(n-1)}$
v_0e^{kz}	$\dfrac{kv_0z}{1-e^{-kz}}$	$\dfrac{v_0}{1-kv_0t_v}$	$\dfrac{1}{kt_v}\log\dfrac{1}{1-kv_0t_v}$
$v_1\tanh(Az+B)$	$\dfrac{Av_1z}{\log\dfrac{\sinh(Az+B)}{\sinh B}}$	$v_1(1+e^{-2Av_1t_v}\operatorname{cosech}^2B)^{-1/2}$	$\dfrac{1}{At_v}\left[\sinh^{-1}(e^{Av_1t_v}\sinh B)-B\right]$
$v_1-\dfrac{A}{z+a}$	$\dfrac{v_1z}{z+\dfrac{A}{v_1}\log\left(1+\dfrac{\beta z}{a}\right)}$ $\beta=\dfrac{v_1}{v_0}$		
$v_0\left(1-\dfrac{z^2}{z_c^2}\right)^{-1/2}$	$\dfrac{2v_0z_cz}{z(z_c^2-z^2)^{1/2}+z_c^2\sin^{-1}(z/z_c)}$		
$v_0(1+A^2z^2)^{1/2}$	$\dfrac{Av_0z}{\sinh^{-1}Az}$	$v_0\cosh Av_0t_v$	$\dfrac{1}{t_v}\sinh Av_0t_v$
$A\left(\dfrac{z}{z+h}\right)^{1/2}$	$\dfrac{Az}{[z(z+h)]^{1/2}+h\tanh^{-1}\left(\dfrac{z}{z+h}\right)^{1/2}}$		
$v_0\cosh Az$	$\dfrac{v_0Az}{\tan^{-1}(\sinh Az)}$	$v_0\sec v_0At_v$	$\dfrac{1}{At_v}\sinh^{-1}(\tan v_0At_v)$

ng rtical-Time	Travel Time from Shot-Point to any Point of Path	Displacement
	$t=t(\theta)$	$x=x(\theta)$
$\left.\begin{matrix}\\ \\ \end{matrix}\right]$ $n\neq 1$	$\dfrac{n}{kv_0 \sin^{n-1}\theta_0}\displaystyle\int_{\theta_0}^{\theta}\sin^{n-2}\theta d\theta$	$\dfrac{n}{k\sin^n\theta_0}\displaystyle\int_{\theta_0}^{\theta}\sin^n\theta d\theta$
	$\dfrac{1}{kv_0}\log\dfrac{\tan(\theta/2)}{\tan(\theta_0/2)}$	$\dfrac{\cos\theta_0-\cos\theta}{k\sin\theta_0}$
)	$\dfrac{2(\theta-\theta_0)}{kv_0\sin\theta_0}$	$\dfrac{1}{2k\sin^2\theta_0}[(2\theta-\sin 2\theta)-(2\theta_0-\sin$
$-1]$	$\dfrac{3(\cos\theta_0-\cos\theta)}{kv_0\sin^2\theta_0}$	$\dfrac{3}{k\sin^3\theta_0}[(\cos\theta_0-\cos\theta)-\frac{1}{3}(\cos^3\theta_0-$
	$\dfrac{nv_0^{n-1}}{A^n\sin^{n-1}\theta_0}\displaystyle\int_{\theta_0}^{\theta}\dfrac{(\sin\theta-\sin\theta_0)^{n-1}}{\sin\theta}d\theta$	$\dfrac{nv_0^n}{A^n\sin^n\theta_0}\displaystyle\int_{\theta_0}^{\theta}\sin\theta(\sin\theta-\sin\theta_0)^n$
	$\dfrac{2v_0}{A^2\sin\theta_0}\left[\theta-\theta_0-(\sin\theta_0)\log\dfrac{\tan(\theta/2)}{\tan(\theta_0/2)}\right]$	$\dfrac{v_0^2}{A^2\sin^2\theta_0}[\theta-\theta_0+2\sin\theta_0\cos\theta-\frac{1}{2}(\sin 2\theta$
$^{1/(n-1)}$	$\dfrac{n}{A^n p^{n-1}}\displaystyle\int_0^{\theta}\sin^{n-2}\theta d\theta$	$\dfrac{n}{A^n p^n}\displaystyle\int_0^{\theta}\sin^n\theta d\theta$
$_0$	$\dfrac{\sin\theta_0(\cot\theta_0-\cot\theta)}{kv_0}$	$\dfrac{\theta-\theta_0}{k}$
$n\,B)-B]$	$(Av_1)^{-1}(\beta^2\sin^2\theta_0-1)^{-1/2}\left[\tan^{-1}\dfrac{\cos\theta_0}{(\beta^2\sin^2\theta_0-1)^{1/2}}-\tan^{-1}\dfrac{\cos\theta}{(\beta^2\sin^2\theta_0-1)^{1/2}}\right]$ $+\dfrac{1}{Av_1}(\tanh^{-1}\cos\theta_0-\tanh^{-1}\cos\theta)$ $\beta=\dfrac{v_1}{v_0}$	$\dfrac{\beta\sin\theta_0}{A(\beta^2\sin^2\theta_0-1)^{1/2}}\left[\tan^{-1}\left(\dfrac{\cos\theta_0}{(\beta^2\sin^2\theta_0-1)^{1/2}}\right.\right.$ $\left.\left.-\tan^{-1}\left(\dfrac{}{(\beta^2 si\right.\right.\right.$
	$\dfrac{a(\beta-1)}{\beta^2 v_0}\left\{\dfrac{\beta\sin\theta_0}{\beta^2\sin^2\theta_0-1}\left[\dfrac{\cos\theta_0}{(\beta-1)\sin\theta_0}-\dfrac{\cos\theta}{\beta\sin\theta_0-\sin\theta}\right]\right.$ $+\dfrac{2\beta^2\sin^2\theta_0-1}{(\beta^2\sin^2\theta_0-1)^{3/2}}\left[\sin^{-1}\left(\dfrac{\beta\sin\theta_0\sin\theta-1}{\beta\sin\theta_0-\sin\theta}\right)\right.$ $\left.\left.-\sin^{-1}\left(\dfrac{\beta\sin^2\theta_0-1}{(\beta-1)\sin\theta_0}\right)\right]+\log\dfrac{\tan(\theta/2)}{\tan(\theta_0/2)}\right\}$ $\beta=\dfrac{v_1}{v_0}$	$\dfrac{A\sin\theta_0}{v_0(\beta^2\sin^2\theta_0-1)}\left\{\beta\sin\theta_0\left[\dfrac{\cos\theta_0}{(\beta-1)\sin\theta_0}-\dfrac{\beta}{}\right.\right.$ $+\dfrac{1}{(\beta^2\sin^2\theta_0-1)^{1/2}}\left[\sin^{-1}\left(\dfrac{\beta}{\beta}\right.\right.$ $\left.\left.\left.-\sin^{-1}\left(\dfrac{\beta}{(\beta-\right.\right.\right.$
	$\dfrac{z_c\sin^2\theta_0}{v_0}\left\{\frac{1}{2}\cot\theta(\cot^2\theta_0-\cot^2\theta)^{1/2}\right.$ $\left.+(1+\frac{1}{2}\cot^2\theta_0)\left[\dfrac{\pi}{2}-\sin^{-1}\left(\dfrac{\cot\theta}{\cot\theta_0}\right)\right]\right\}$	$z_c\sin\theta_0\left[\dfrac{\pi}{2}-\sin^{-1}\left(\dfrac{\cot\theta}{\cot\theta_0}\right)\right.$
	$\dfrac{1}{Av_0}[K(\cos\theta_0)-F(\psi,\cos\theta_0)]$ $\psi=\sin^{-1}(\sec\theta_0\cos\theta)$	$\dfrac{1}{A\sin\theta_0}\left[E\left(\dfrac{\pi}{2},\cos\theta_0\right)-E(\psi,\right.$ co $\psi=\sin^{-1}$
	$\dfrac{hp\sin\theta\cos\theta}{(p^2A^2-\sin^2\theta)(1-p^2A^2)}$ $+\dfrac{h(2p^2A^2-1)}{2A(p^2A^2-1)^{3/2}}\left[\dfrac{\pi}{2}-\sin^{-1}\left(\dfrac{p^2A^2-(2p^2A^2-1)\sin^2\theta}{p^2A^2-\sin^2\theta}\right)\right]$	$\dfrac{hp^2A^2\sin\theta\cos\theta}{(p^2A^2-\sin^2\theta)(1-p^2A^2)}$ $+\dfrac{hpA}{2(p^2A^2-1)^{3/2}}\left[\dfrac{\pi}{2}-\sin^{-1}\left(\dfrac{p^2A^2-(2p^2A^2\right.\right.$ p^2A^2-s
At_0)	$\dfrac{1}{Av_0}\left[\dfrac{\pi}{2}-\tan^{-1}\left(\dfrac{\sin\theta_0\cos\theta}{(\cos^2\theta_0-\cos^2\theta)^{1/2}}\right)\right]$	$\dfrac{1}{A}\left[\dfrac{\pi}{2}-\sin^{-1}\left(\dfrac{\cos\theta}{\cos\theta_0}\right)\right]$

TABLE I

ASED ON A GIVEN INSTANTANEOUS-VELOCITY—DEPTH FUNCTION

Displacement	Vertical Depth to any Point of Path	Depth—Vertical-Time Function	Surf
$x=x(\theta)$	$z=z(\theta)$	$z=z(t_v)$	
$\frac{n}{k\sin^n\theta_0}\int_{\theta_0}^{\theta}\sin^n\theta d\theta$	$\frac{1}{k}\left(\frac{\sin^n\theta}{\sin^n\theta_0}-1\right)$	$\frac{1}{k}\left[\left(1+\frac{(n-1)kv_0}{n}t_v\right)^{n/(n-1)}-1\right]$ $n\neq 1$	$\frac{}{kv}$
$\frac{\cos\theta_0-\cos\theta}{k\sin\theta_0}$	$\frac{1}{k}\left(\frac{\sin\theta}{\sin\theta_0}-1\right)$	$\frac{1}{k}\left(e^{kv_0t_v}-1\right)$	
$\frac{}{^2\theta_0}[(2\theta-\sin 2\theta)-(2\theta_0-\sin 2\theta_0)]$	$\frac{1}{k}\left(\frac{\sin^2\theta}{\sin^2\theta_0}-1\right)$	$v_0t_v(1+\frac{1}{2}kv_0t_v)$	
$[(\cos\theta_0-\cos\theta)-\frac{1}{2}(\cos^2\theta_0-\cos^2\theta)]$	$\frac{1}{k}\left(\frac{\sin^3\theta}{\sin^3\theta_0}-1\right)$	$\frac{1}{k}[(1+\frac{3}{2}kv_0t_v)^{3/2}-1]$	
$\frac{^n}{^n\theta_0}\int_{\theta_0}^{\theta}\sin\theta(\sin\theta-\sin\theta_0)^{n-1}d\theta$	$\left[\frac{v_0(\sin\theta-\sin\theta_0)}{A\sin\theta_0}\right]^n$		$\frac{2nv_0^n}{A^n\sin^n}$
$-\theta_0+2\sin\theta_0\cos\theta-\frac{1}{2}(\sin 2\theta+\sin 2\theta_0)]$	$\left[\frac{v_0(\sin\theta-\sin\theta_0)}{A\sin\theta_0}\right]^2$	$t_v=\frac{2}{A^2}\left[Az^{1/2}-v_0\log\left(1+\frac{Az^{1/2}}{v_0}\right)\right]$	$\frac{4v_0}{A^2\sin\theta}$
$\frac{n}{A^np^n}\int_0^{\theta}\sin^n\theta d\theta$	$\frac{\sin^n\theta}{A^np^n}$	$\left(\frac{n-1}{n}\cdot At_v\right)^{n/(n-1)}$	
$\frac{\theta-\theta_0}{k}$	$\frac{1}{k}\log\frac{\sin\theta}{\sin\theta_0}$	$\frac{1}{k}\log\frac{1}{1+kv_0t_v}$	
$^{1/2}\left[\tan^{-1}\left(\frac{\cos\theta_0}{(\beta^2\sin^2\theta_0-1)^{1/2}}\right)-\tan^{-1}\left(\frac{\cos\theta}{(\beta^2\sin^2\theta_0-1)^{1/2}}\right)\right]$ $\beta=\frac{v_1}{v_0}$	$\frac{1}{A}\left[\tanh^{-1}\left(\frac{\sin\theta}{\beta\sin\theta_0}\right)-B\right]$ $\beta=\frac{v_1}{v_0}$	$\frac{1}{A}[\sinh^{-1}(e^{Av_1t_v}\sinh B)-B]$	$\frac{2}{Av_1(\beta^2\sin^2\theta_0-$
$\beta\sin\theta_0\left[\frac{\cos\theta_0}{(\beta-1)\sin\theta_0}-\frac{\cos\theta}{\beta\sin\theta_0-\sin\theta}\right]$ $\frac{1}{\sin^2\theta_0-1)^{1/2}}\left[\sin^{-1}\left(\frac{\beta\sin\theta_0\sin\theta-1}{\beta\sin\theta_0-\sin\theta}\right)-\sin^{-1}\left(\frac{\beta\sin^2\theta_0-1}{(\beta-1)\sin\theta_0}\right)\right]\Big\}$ $\beta=\frac{v_1}{v_0}$	$\frac{a(\sin\theta-\sin\theta_0)}{\beta\sin\theta_0-\sin\theta}$ $\beta=\frac{v_1}{v_0}$	$t_v=\frac{1}{v_1}\left[z+\frac{A}{v_1}\log\left(1+\frac{\beta z}{a}\right)\right]$ $\beta=\frac{v_1}{v_0}$	$\frac{2a(\beta-1)}{\beta^2v_0}\Big\{\log$ $+\frac{2\beta^2\sin}{(\beta^2\sin^2\theta}$
$_0\left[\frac{\pi}{2}-\sin^{-1}\left(\frac{\cot\theta}{\cot\theta_0}\right)\right]$	$z_c(1-\sin^2\theta_0\operatorname{cosec}^2\theta)^{1/2}$	$t_v=\frac{1}{2v_0z_c}\left[z(z_c^2-z^2)^{1/2}+z_c^2\sin^{-1}\left(\frac{z}{z_c}\right)\right]$	
$E\left(\frac{\pi}{2},\cos\theta_0\right)-E(\psi,\cos\theta_0)\Big]$ $\psi=\sin^{-1}(\sec\theta_0\cos\theta)$	$\frac{1}{A}(\sin^2\theta\operatorname{cosec}^2\theta_0-1)^{1/2}$	$\frac{1}{A}\sinh Av_0t_v$	
$^2A^2)$ $-\sin^{-1}\left(\frac{p^2A^2-(2p^2A^2-1)\sin^2\theta}{p^2A^2-\sin^2\theta}\right)\Big]$	$\frac{h\sin^2\theta}{p^2A^2-\sin^2\theta}$	$t_v=\frac{1}{A}\left\{[z(z+h)]^{1/2}+h\tanh^{-1}\left(\frac{z}{z+h}\right)^{1/2}\right\}$	
$\frac{\pi}{2}-\sin^{-1}\left(\frac{\cos\theta}{\cos\theta_0}\right)\Big]$	$\frac{1}{A}\cosh^{-1}\left(\frac{\sin\theta}{\sin\theta_0}\right)$	$\frac{1}{A}\sinh^{-1}(\tan v_0At_v)$	

Surface-to-Surface Travel Time	Range	Depth to Maximum Penetration
T	X	Z
$\frac{2n}{kv_0 \sin^{n-1}\theta_0}\int_{\theta_0}^{\pi/2} \sin^{n-2}\theta d\theta$	$\frac{2n}{k \sin^n \theta_0}\int_{\theta_0}^{\pi/2} \sin^n \theta d\theta$	$\frac{1}{k}(\operatorname{cosec}^n \theta_0 - 1)$
$\frac{2}{kv_0}\log \cot(\theta_0/2)$	$\frac{2\cot\theta_0}{k}$	$\frac{1}{k}(\operatorname{cosec}\theta_0 - 1)$
$\frac{4}{kv_0 \sin\theta_0}\left(\frac{\pi}{2}-\theta_0\right)$	$\frac{1}{k\sin^2\theta_0}(\pi - 2\theta_0 + \sin 2\theta_0)$	$\frac{1}{k}\cot^2\theta_0$
$\frac{6\cos\theta_0}{kv_0 \sin^2\theta_0}$	$\frac{6}{k\sin^3\theta_0}(\cos\theta_0 - \frac{1}{3}\cos^3\theta_0)$	$\frac{1}{k}(\operatorname{cosec}^3\theta_0 - 1)$
$\frac{2nv_0^{n-1}}{A^n \sin^{n-1}\theta_0}\int_{\theta_0}^{\pi/2}\frac{(\sin\theta - \sin\theta_0)^{n-1}}{\sin\theta}d\theta$	$\frac{2nv_0^n}{A^n \sin^n\theta_0}\int_{\theta_0}^{\pi/2}\sin\theta\,(\sin\theta - \sin\theta_0)^{n-1}d\theta$	$\left[\frac{v_0}{A}(\operatorname{cosec}\theta_0 - 1)\right]^n$
$\frac{4v_0}{A^2\sin\theta_0}\left[\frac{\pi}{2}-\theta_0-(\sin\theta_0)\log\cot\frac{\theta_0}{2}\right]$	$\frac{v_0^2}{A^2\sin^2\theta_0}(\pi - 2\theta_0 - \sin 2\theta_0)$	$\left[\frac{v_0}{A}(\operatorname{cosec}\theta_0 - 1)\right]^2$
$\frac{n\pi^{1/2}}{A^n p^{n-1}}\cdot\frac{\Gamma\left(\frac{n-1}{2}\right)}{\Gamma\left(\frac{n}{2}\right)}$	$\frac{n\pi^{1/2}}{A^n p^n}\cdot\frac{\Gamma\left(\frac{n+1}{2}\right)}{\Gamma\left(\frac{n}{2}+1\right)}$	$\frac{1}{A^n p^n}$
$\frac{2\cos\theta_0}{kv_0}$	$\frac{1}{k}(\pi - 2\theta_0)$	$\frac{1}{k}\log\operatorname{cosec}\theta_0$
$\frac{2}{A(\beta^2\sin^2\theta_0-1)^{1/2}}\tan^{-1}\frac{\cos\theta_0}{(\beta^2\sin^2\theta_0-1)^{1/2}} + \frac{2}{Av_1}\tanh^{-1}\cos\theta_0$ $\beta=\frac{v_1}{v_0}$	$\frac{2\beta\sin\theta_0}{A(\beta^2\sin^2\theta_0-1)^{1/2}}\tan^{-1}\frac{\cos\theta_0}{(\beta^2\sin^2\theta_0-1)^{1/2}}$ $\beta=\frac{v_1}{v_0}$	$\frac{1}{A}[\coth^{-1}(\beta\sin\theta_0) - B]$ $\beta=\frac{v_1}{v_0}$
$\frac{(\beta-1)}{\beta^2 v_0}\left\{\log\cot\frac{\theta_0}{2} + \frac{\beta\cos\theta_0}{(\beta-1)(\beta^2\sin^2\theta_0-1)} + \frac{2\beta^2\sin^2\theta_0-1}{(\beta^2\sin^2\theta_0-1)^{3/2}}\left[\frac{\pi}{2}-\sin^{-1}\frac{\beta\sin^2\theta_0-1}{(\beta-1)\sin\theta_0}\right]\right\}$ $\beta=\frac{v_1}{v_0}$	$\frac{2a(\beta-1)\sin\theta_0}{\beta^2\sin^2\theta_0-1}\left\{\frac{\beta\cos\theta_0}{\beta-1} + \frac{1}{(\beta^2\sin^2\theta_0-1)^{1/2}}\left[\frac{\pi}{2}-\sin^{-1}\frac{\beta\sin^2\theta_0-1}{(\beta-1)\sin\theta_0}\right]\right\}$ $\beta=\frac{v_1}{v_0}$	$\frac{a(1-\sin\theta_0)}{\beta\sin\theta_0-1}$ $\beta=\frac{v_1}{v_0}$
$\frac{\pi z_c}{2v_0}(1+\sin^2\theta_0)$	$\pi z_c \sin\theta_0$	$z_c\cos\theta_0$
$\frac{2}{Av_0}K(\cos\theta_0)$	$\frac{2}{A\sin\theta_0}E\left(\frac{\pi}{2},\cos\theta_0\right)$	$\frac{1}{A}\cot\theta_0$
$\frac{\pi h(2p^2A^2-1)}{A(p^2A^2-1)^{3/2}}$	$\frac{\pi pAh}{(p^2A^2-1)^{3/2}}$	$\frac{h}{p^2A^2-1}$
$\frac{\pi}{v_0 A}$	$\frac{\pi}{A}$	$\frac{1}{A}\cosh^{-1}(\operatorname{cosec}\theta_0)$

on the line $z=-1/k$. (The negative sign on the right-hand side of the ray-path x-equation results from the fact that θ, as defined in Figure 1, is the angle between the normal to the ray-path and the negative direction of the x-axis; whereas in the standard parametric equations of a circle θ is measured relative to the positive direction of the x-axis.)

The cartesian equation of the ray-path is obtained by eliminating θ from the parametric equations. Thus by squaring and adding:

$$(x - \cot \theta_0/k)^2 + (z + 1/k)^2 = 1/(k^2 \sin^2 \theta_0).$$

Another simple way of showing that the ray-path is a circle is afforded by the radius of curvature $\rho=v_0/(v'(z) \sin \theta_0)$, which in the present case reduces to $1/(k \sin \theta_0)$. Since this is a constant for the given path, the ray-path is a circle of radius $1/(k \sin \theta_0)$. This proof has been given by Gutenberg (5), Fu (6), and van Melle (7). Matthews (8) provides another geometrical proof that the ray-path is a circle.

Wave-front. By definition the wave-front is the locus of constant-t values. Its equation is obtained by eliminating θ_0 from the equations for x, z, and t. In the present case the parametric equations of the wave-front are found to be

$$x = (1/k) \sinh kv_0t \cdot \sin \theta,$$
$$z - (\cosh kv_0t - 1)/k = (1/k) \sinh kv_0t \cos \theta,$$

whence the wave-front is a circle of radius $(1/k) \sinh kv_0t$ centered at $x=0$, $z=(\cosh kv_0t-1)/k$. This defines the position of the wave-front at any instant t.

Analyses of the linear velocity-depth function essentially geometrical in nature will be found in Nettleton (9) and Heiland (10). A more intensive investigation of the geometrical properties is given by van Melle (7). The same function has also been treated in detail by Slotnick (11), Ewing and Leet (12), and Roman (13). Lyons (14) has given an application to weathering problems.

Computation Charts and Mechanical Devices. A wave-front ray-path chart for the computation of displacements and depths is easily constructed using the data for the families of circles described above. A description of such a chart is given by Nettleton (9), Soske (15), and Jakosky (16). Soske (15) also describes an alternative computation scheme comprising separate charts for depth, dip, and displacement. Some additional charts are given by Agocs (17).

Peterson (18) gives a chart, based on a conformal transformation in the complex plane, wherein the original wave-front circles are transformed into a set of concentric circles (centered at the origin) and the original ray-path circles are transformed into a set of radial straight lines passing through the origin. The original rectilinear coordinate system, however, transforms into two orthogonal sets of circles.

Mechanical devices based on these charts have been constructed by Daly (19), corresponding to the standard type of wave-front ray-path chart, and by Wolf

(20), corresponding to Peterson's transformed chart. Slide rules are described by Fillippone (21) and Mansfield (22).

(c) $v=v_0(1+kz)^{1/2}$. The velocity is a parabolic function of depth. This is a special case of (a) with $n=2$, and has enjoyed a certain degree of popularity in the literature. From Table I the parametric equations for displacement and depth are

$$x + c = b(2\vartheta - \sin 2\theta),$$

$$z + 1/k = b(1 - \cos 2\theta),$$

where $b=1/(2k \sin^2 \theta_0)$, $c=(2\theta_0-\sin 2\theta_0)/(2k \sin^2 \theta_0)$. The ray-path is thus a cycloid, which can be considered as generated by a circle rolling on the lower side of the line $z=-1/k$, with initial point of contact at $x=-(2\theta_0-\sin 2\theta_0)/(2k \sin^2 \theta_0)$. The radius of the rolling circle is $b=1/(2k \sin^2 \theta_0)$.

This function has been discussed by Houston (23) and Ramspeck (24), and used by Rice (25) as a basis for comparing several standard computing techniques, and by Stolken (26) in an analysis of the errors in straight-ray computing methods.

(d) $v=v_0(1+kz)^{1/3}$. This is a special case of (a) with $n=3$, and is included to provide additional illustration of the reduction of the formulas derived for the general case.

(e) $v=v_0+Az^{1/n}$. This function bears a superficial resemblance to the binomial expression of case (a). However, the analysis leads to considerably more complicated expressions for displacement, travel time, etc. Aside from brief mention by Mott-Smith (1), little has been written about this function. Rutherford (27) has computed the depth to a high-speed layer for the case where the overburden velocity is of this form with exponent $n=2$.

(f) $v=Az^{1/n}$. This special case of (e) with $v_0=0$ represents an important group of functions having zero initial velocity. Some of the properties have been discussed by Goguel (28). The functions are finding increasing use in applications to weathering problems.

(g) $v=v_0e^{kz}$. The velocity increases exponentially with depth (for $k>0$). An analysis has been given by Slotnick (11), and an application to the fitting of empirical data discussed by Mott-Smith (1).

(h) $v=v_1 \tanh (Az+B)$. The velocity increases from $v_0(=v_1 \tanh B)$ following the form of the hyperbolic tangent function to a limiting value of v_1. Muskat (3) has studied this case in the inverse form

$$z = a \log \frac{(v_1 + v)(v_1 - v_0)}{(v_1 - v)(v_1 + v_0)}.$$

(i) $v=v_1-[A/(z+a)]$. The function represents a rectangular hyperbola with center at $v=v_1$, $z=-a$. The velocity increases from $v_0(=v_1-(A/a))$ hyperbolically to a limiting value of v_1. Muskat (3) uses the inverse function $z=a(v_1-v_0)/(v_1-v)$.

Instantaneous-Velocity—Vertical-Time Function	Corresponding Average-Velocity—Vertical-Time Function	Corresponding Instantaneous-Velocity—Depth Function	Correspondi Average-Veloci Depth Funct
$v=v(t_v)$	$v_a=v_a(t_v)$	$v=v(z)$	$v_a=v_a(z)$
$v_0(1+Kt_v)^{1/n}$	$\frac{nv_0}{(n+1)K}\cdot\frac{(1+Kt_v)^{(n+1)/n}-1}{t_v}$	$v_0\left(1+\frac{K(n+1)}{v_0 n}z\right)^{1/(n+1)}$	$\frac{Kz}{\left(1+\frac{K(n+1)}{v_0 n}z\right)^{n/}}$
$v_0+Bt_v^{1/n}$	$v_0+\frac{nB}{n+1}t_v^{1/n}$	$z=\left(\frac{v-v_0}{B}\right)^n\left(\frac{nv+v_0}{n+1}\right)$	$z=v_a\left[\frac{(n+1)(v_a-$ nB
$v_0+Bt_v^{1/2}$	$v_0+\frac{2}{3}Bt_v^{1/2}$	$z=\frac{1}{3B^2}(v-v_0)^2(2v+v_0)$	$z=v_a\left[\frac{3(v_a-v_0}{2B}\right.$
$v_0e^{At_v}$	$\frac{v_0(e^{At_v}-1)}{At_v}$	v_0+Az	$\frac{Az}{\log\left(1+\frac{Az}{v_0}\right.}$

TABLE II

RELATIONS BASED ON A GIVEN INSTANTANEOUS-VELOCI

Corresponding Average-Velocity—Depth Function	Travel Time from Shot-point to any Point of Path	Displacement	Vertical Depth t
$v_a = v_a(z)$	$t(\theta)$	$x(\theta)$	
$\dfrac{Kz}{\left(\dfrac{K(n+1)}{v_0 n} z\right)^{n/(n+1)} - 1}$	$\dfrac{n}{K \sin^n \theta_0} \displaystyle\int_{\theta_0}^{\theta} \sin^{n-1} \theta d\theta$	$\dfrac{n v_0}{K \sin^{n+1} \theta_0} \displaystyle\int_{\theta_0}^{\theta} \sin^{n+1} \theta d\theta$	$\dfrac{n v_0}{(n+1)K}$ (
$v_a \left[\dfrac{(n+1)(v_a - v_0)}{nB}\right]^n$	$\dfrac{n v_0^n}{B^n \sin^n \theta_0} \displaystyle\int_{\theta_0}^{\theta} (\sin\theta - \sin\theta_0)^{n-1} d\theta$	$\dfrac{n v_0^{n+1}}{B^n \sin^{n+1} \theta_0} \displaystyle\int_{\theta_0}^{\theta} \sin^2\theta (\sin\theta - \sin\theta_0)^{n-1} d\theta$	$\dfrac{v_0^{n+1}}{(n+1)B^n \sin^{n+1} \theta_0}$ (sin
$= v_a \left[\dfrac{3(v_a - v_0)}{2B}\right]^2$	$\dfrac{2v_0^2}{B^2 \sin^2 \theta_0} [\cos\theta_0 - \cos\theta - (\theta - \theta_0) \sin\theta_0]$	$\dfrac{2v_0^3}{B^2 \sin^2 \theta_0} \left\{ \tfrac{1}{2}(\cos^3\theta - \cos^3\theta_0) - (\cos\theta - \cos\theta_0) - \dfrac{\sin\theta_0}{2} [\theta - \theta_0 - \tfrac{1}{2}\sin 2\theta + \tfrac{1}{2}\sin 2\theta_0] \right\}$	$\dfrac{v_0^3}{3B^2 \sin^3 \theta_0}$ (2 sin^3 θ
$\dfrac{Az}{\log\left(1 + \dfrac{Az}{v_0}\right)}$	$\dfrac{1}{A} \cdot \log \dfrac{\tan(\theta/2)}{\tan(\theta_0/2)}$	$\dfrac{v_0}{A \sin\theta_0} (\cos\theta_0 - \cos\theta)$	$\dfrac{v_0}{A}$ (si sin

TABLE II

NSTANTANEOUS-VELOCITY—VERTICAL-TIME FUNCTION

Vertical Depth to any Point of Path	Depth—Vertical-Time Function	Surface-to-Surface Travel Time	
$z(\theta)$	$z=z(t_v)$	T	
$\frac{nv_0}{(n+1)K}\left(\frac{\sin^{n+1}\theta}{\sin^{n+1}\theta_0}-1\right)$	$\frac{nv_0}{(n+1)K}\left[(1+Kt_v)^{(n+1)/n}-1\right]$	$\frac{2n}{K\sin^n\theta_0}\int_{\theta_0}^{\pi/2}\sin^{n-1}\theta d\theta$	
$\frac{{v_0}^{n+1}}{(n+1)B^n\sin^{n+1}\theta_0}(\sin\theta-\sin\theta_0)^n(n\sin\theta+\sin\theta_0)$	$t_v\left(v_0+\frac{nB}{n+1}t_v^{1/n}\right)$	$\frac{2n{v_0}^n}{B^n\sin^n\theta_0}\int_{\theta_0}^{\pi/2}(\sin\theta-\sin\theta_0)^{n-1}d\theta$	$\frac{2}{B^n}$
$\frac{{v_0}^3}{3B^2\sin^3\theta_0}(2\sin^3\theta+\sin^3\theta_0-3\sin^2\theta\sin\theta_0)$	$t_v\left(v_0+\frac{2B}{3}t_v^{1/2}\right)$	$\frac{4{v_0}^2}{B^2\sin^2\theta_0}\left[\cos\theta_0-\left(\frac{\pi}{2}-\theta_0\right)\sin\theta_0\right]$	$\frac{{v_0}^3}{B^2\sin^3\theta_0}$
$\frac{v_0}{A}\left(\frac{\sin\theta}{\sin\theta_0}-1\right)$	$\frac{v_0}{A}(e^{At_v}-1)$	$\frac{2}{A}\log\cot\frac{\theta_0}{2}$	

	Range	Depth to Maximum Penetration
	X	Z
	$\frac{2nv_0}{K\sin^{n+1}\theta_0}\int_{\theta_0}^{\pi/2}\sin^{n+1}\theta d\theta$	$\frac{nv_0}{(n+1)K}(\operatorname{cosec}^{n+1}\theta_0-1)$
	$\frac{2nv_0^{n+1}}{B^n\sin^{n+1}\theta_0}\int_{\theta_0}^{\pi/2}\sin^2\theta(\sin\theta-\sin\theta_0)^{n-1}d\theta$	$\frac{v_0^{n+1}}{(n+1)B^n\sin^{n+1}\theta_0}(1-\sin\theta_0)^n(n+\sin\theta_0)$
	$\frac{v_0^2}{B^2\sin^2\theta_0}\left[4\cos\theta_0-\frac{4}{3}\cos^2\theta_0+\sin\theta_0(2\theta_0-\sin 2\theta_0-\pi)\right]$	$\frac{v_0^2}{3B^2\sin^2\theta_0}(1-\sin\theta_0)^2(2+\sin\theta_0)$
	$\frac{2v_0}{A}\cot\theta_0$	$\frac{v_0}{A}(\operatorname{cosec}\theta_0-1)$

(j) $v=v_0[1-(z/z_c)^2]^{-1/2}$. The velocity approaches infinity at the finite depth $z=z_c$. A brief discussion will be found in Muskat (3).

(k) $v=v_0(1+A^2z^2)^{1/2}$. This function bears a superficial resemblance to the parabolic function considered in case (c); however the analysis is here considerably more complicated. This case is also given brief mention by Muskat (3).

(l) $v=A[z/(z+h)]^{1/2}$. The velocity increases from zero to a limiting value of A. This function has been used by Goguel (28).

(m) $v=v_0 \cosh Az$. Slichter (29) has shown that the velocity-depth function must be of this form to yield a $T-X$ curve consisting of one point only; that is, all the ray-paths are traversed in the same time and meet at the same point on the surface. Slichter attacked the problem by using the Herglotz-Bateman integral equation wherein the $T-X$ curve is specified and the velocity-depth function deduced therefrom. We treat this case from the inverse point of view, assuming the velocity function as given and deducing the required relations as in the preceding examples. Note that by Table I the values of T and X are constants; i.e., independent of the ray-path. Hence all the (surface-to-surface) paths are represented by a single point on the $T-X$ curve.

PART II

Relations based on a given instantaneous-velocity—vertical-time function

In the introduction the equivalence between velocity-depth functions and velocity—vertical-time functions was noted. In certain cases the latter may possess advantages over the former, as emphasized by Mott-Smith (1) for functions of the type $v=v_0+Bt_v^{1/n}$. To facilitate the study of such functions the basic relations analogous to those of Part I are presented here and the results for a number of cases incorporated in Table II.

The required relations are obtained from those in Part I by suitable modification. Thus the parametric equations for the displacement, x, and travel time, t, are:

$$x = \int_{\theta_0}^{\theta} \frac{\sin^2 \theta d\theta}{p^2 v'(t_v)}, \tag{2.1}$$

$$t = \int_{\theta_0}^{\theta} \frac{d\theta}{p v'(t_v)}. \tag{2.2}$$

Note that $v'(t_v) \equiv dv/dt_v$ must be expressed as a function of θ before the integrations can be performed.

The relation for depth explicitly in terms of vertical travel time is

$$z = \int_0^{t_v} v(t_v) dt_v. \tag{2.3}$$

The equation for depth in terms of θ as parameter,

$$z = z(\theta), \tag{2.4}$$

is obtained by eliminating t_v from the $z-t_v$ relation (2.3) and the given velocity function $v=v(t_v)$ together with the relation $pv=\sin\theta$.

The range, X, surface-to-surface travel time, T, and maximum depth of penetration, Z, are given by:

$$X = 2\int_{\theta_0}^{\pi/2} \frac{\sin^2\theta d\theta}{p^2 v'(t_v)} \tag{2.5}$$

$$T = 2\int_{\theta_0}^{\pi/2} \frac{d\theta}{pv'(t_v)} \tag{2.6}$$

$$Z = z(\pi/2). \tag{2.7}$$

The corresponding average velocity as a function of vertical time is

$$v_a(t_v) = \frac{\int_0^{t_v} v(t_v)dt_v}{t_v}. \tag{2.8}$$

The instantaneous-velocity—depth function corresponding to the given instantaneous-velocity—vertical-time function is obtained by eliminating t_v from the equations $v=v(t_v)$ and $z=z(t_v)$. If t_v cannot be eliminated the pair of equations $v=v(t_v)$ and $z=z(t_v)$ should still be considered as parametric equations relating v and z in terms of t_v as parameter.

Similarly the corresponding average-velocity—depth function is obtained by eliminating t_v from (2.3) and (2.8).

The above analysis constitutes the basis for the computation of Table II. In view of the equivalence of the velocity-depth and velocity—vertical-time functions as given in the first and third columns of Table I, it was considered unnecessary to incorporate all of these functions in Table II. However, to illustrate the relations of Part II and to emphasize once more the equivalence of the two representations, the binomial function $v_0(1+Kt_v)^{1/n}$ is included corresponding to case (a) of Part I with exponent $1/(n+1)$, and the exponential function $v_0e^{At_v}$ corresponding to the linear velocity-depth function of Part I. The important case treated here which has no equivalent in Table I is $v=v_0+Bt_v^{1/n}$.

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THE EFFECT OF PRESSURE ON THE REDUCTION OF PORE VOLUME OF CONSOLIDATED SANDSTONES*

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ABSTRACT

The changes in pore volume of jacketed dry sandstone samples have been measured under hydrostatic pressures over the range 50 to 1,000 bars (14,504 psi). The percent change in pore volume at each pressure and the pressure coefficient of change of pore volume have been computed. All measurements were made at room temperature.

The total change in pore volume when the hydrostatic pressure was increased from 50 to 1,000 bars was found to be about 7.5 percent of the pore volume for a sample of Steven sandstone (porosity 18.5 percent) and approximately 3.0 percent of the pore volume for a sample of Berea sandstone (porosity 19.4 percent).

The coefficient of change of pore volume with pressure is found to decrease rather rapidly with increasing pressure up to around 500 bars. Thus pressure changes applied to rock become much more important when the original geostatic load on the rock is small.

INTRODUCTION

The compressibility of oil-bearing formations could be an important factor in estimating the amount of fluid in the reservoir and the ultimate reservoir performance from physical measurements made on the reservoir rock. Compressibility data might also be helpful in interpreting the change of velocity of seismic waves due to a change in density and elastic constants of the material and in the use of neutron logging devices for measuring porosity of rocks *in situ*. A change in porosity in the reservoir rock caused by compressive forces would be expected to affect other characteristics of the material, such as permeability.

The compressibilities up to 3,000 psi of unconsolidated sands have been measured by Botset and Reed (1935); the compressibilities at high pressures of several rocks and minerals, not including any sandstones, have been investigated by Adams and Williamson (1923); and the compressibilities of several rocks, including one sandstone, have been measured by Zisman (1933). Bureau of Mines engineers have made compressibility tests on water-saturated samples from four consolidated sandstones at pressures up to 8,000 psi (Carpenter and Spencer, 1940).

The method described in this investigation consists of applying hydrostatic pressure to jacketed dry sandstone samples up to 1,000 bars. The changes in volume of the air in the pores of the sample are measured.

GENERAL CONSIDERATIONS OF COMPRESSIBILITY OF SANDSTONES

The materials and constructions of sandstones are so different for different samples that any investigation to determine the quantitative effect of each of

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the factors which control the compressibility would necessitate a detailed chemical and microscopic examination of each sample. Indeed, as Adams and Williamson (1923) have said, " . . . the change of compressibility at low pressures" (a few hundred bars), "while connected with the admixture of minerals of different compressibility and with a looseness of structure existing in some coarse-grained rocks, can not with certainty be predicted in advance." At pressures of 14,504 and 29,008 psi these authors were able to compute with reasonable accuracy the bulk moduli of several porous rocks from the values of their constituent materials. However, these pressures are above the range of pressures usually found in producing oil reservoirs.

The compaction of porous rocks has been suggested by some geologists as a factor in the accumulation of oil and gas (Van Tuyl, Parker, and Skeeters, 1945). The compaction of reservoir rocks due to the weight of the overburden has also been suggested by some as the source of fluid pressures underground, but this view has been criticized (Lewis, 1934).

It seems reasonable to expect that the amount of compaction which a sandstone sample undergoes under laboratory conditions such as those described in this paper is in a large part determined by its pressure history. A rock of loose structure containing grains with many sharp corners could not have previously borne a heavy burden. A detailed study of factors which over a long period of time cause the reduction of porosity in sandstones has been made by Taylor (1950).

The measurements made here are of the changes of pore volume with pressure of a conglomerate mass of grain particles surrounded by an impermeable covering, so that hydrostatic pressure is applied directly only to the outside layer of the rock. It is assumed that this pressure is transmitted by the grains uniformly throughout these small samples. The compressibility of uncovered rock samples has been investigated by Zisman (1933), allowing the pressure-transmitting fluid to fill the pores, and in effect measuring the compressibility of all the individual particles. His results under these conditions show a very small variation in compressibility of an uncovered sandstone in the pressure range of 0 to 720 kg/cm^2, however his value is more than half of our value of the pressure coefficient of pore volume change of a jacketed Berea sandstone sample. The measurements by Zisman on the same sample when covered with a metal jacket and when uncovered show that the two compressibilities approach each other at high pressures and are very nearly the same at 720 kg/cm^2 on the sandstone sample used by him. This difference in the elastic constants of enclosed and unenclosed rocks was also noted by Hughes and Jones (1950) when measuring wave-velocities in rocks, and the effect of pore volume in the rock on wave-velocities was discussed.

The change in pore volume with pressure of an enclosed sample takes into account only the effect of closing cracks and pores in the sample because of compressing, breaking, and rearranging grains. To similate conditions existing in

an oil reservoir it would of course be necessary to have a fluid pressure in the pores equal to the fluid pressure in the reservoir, and a pressure applied to the outside layers of the sample equal to the geostatic load. These conditions are difficult to obtain experimentally, but it should be pointed out that there are possibly two significant volume changes when the fluid pressure in a reservoir is decreased. Generally the vertical geostatic load on the reservoir rock is increased, let us say by the same amount the fluid pressure is decreased, therefore tending to force the grains close together and reduce the pore volume. But there is also an expansion of grains at points where they are not in contact with other grains when the fluid pressure is decreased. Therefore pore volume is decreased further. Also, the rock pressure is apt to be applied mostly to the least compressible grains, forming the most rigid framework possible, whereas fluid pressure is applied to all grains. The laboratory conditions described here measure the change in pore volume due to an increase in differential pressure between the pressure caused by the geostatic gradient and the fluid pressure, which should give results sufficiently accurate for any application, but these conditions do not take into account the small volume change that would occur when individual grains expand under a decreasing fluid pressure.

EXPERIMENTAL PROCEDURE

Preparation of Cores

Cores of consolidated sedimentary rocks were drilled and sawed into cylinders approximately one inch in diameter and three inches long. The cores were then dried for several hours at a temperature of 110°C; the dimensions of the core were recorded, and they were weighed before being placed in metal jackets.

Jacketing the Cores

A rectangular sheet of copper having a thickness of 0.006 inch was cut for each sample and the sample rolled in the sheet, leaving an overlapping seam down the axis of the cylinder and about one-quarter inch of the copper extending over each end of the core. The sample and copper jacket were then placed on the head as shown in Figure 4, and a snugly fitting neoprene jacket was pulled on over the copper. This served to prevent leaks at low pressures when the copper, core, and head were not pressed tightly together. The jacketed sample was then placed in the pressure cylinder and subjected to 15,000 psi pressure for about 20 minutes. Observation of the copper jacket after each sample was removed from the pressure cylinder revealed that the copper was fitted in the outside pores of the sample very tightly.

Method of Measuring Porosity

The bulk volume of the samples was determined from physical dimensions taken by the use of calipers. A modified Boyle's Law apparatus as shown in Figure 6 was used to determine pore volume. A change in height of the mercury

in the tubes resulted in a change of pressure and volume of the air above the mercury in the right system, from which the volume of this system can be computed, using:

$$p_1v_1 = p_2v_2, \text{ assuming, of course, isothermal changes,}$$

or,

$$(h_1 - k_1)(V - F_1) = (h_2 - k_2)(V - F_2),$$

where

h = height of mercury in the left tube
k = height of mercury in the right tube,
V = Total volume of right system above the zero-point,
F = volume of mercury in the right tube above the zero-point.

Several sets of volume and pressure readings were taken on each sample so that an average could be obtained for the value of V, the unknown volume. A period of several minutes was allowed each time after the mercury level was changed to allow the system to come to temperature equilibrium.

The volume of the right manometer tube was determined accurately by filling it with mercury, drawing out small, weighed amounts, and noting the corresponding change in height of the mercury column by the use of a cathetometer. A straight-line formula was obtained for the volume of the mercury in the tube as a function of height, and a curve was drawn representing the deviations from straight line. This enabled the volume of mercury in the tube to be read with an accuracy of ± 0.001 cm^3.

The volume of a blank system was determined by placing the steel plug shown under the sample in Figure 4 directly against the head. The pore volume of each sample was then the difference between the volume of the right system with the sample in place minus the volume of the system with no sample in place.

Method of Measuring Change in Pore Volume

The changes in pore volume of the samples were measured by the apparatus shown in Figure 5. The samples had previously been subjected to a pressure of 500 bars for 2 or 3 hours while the pore volume was being determined and to the pressure applied just after jacketing as described before. A mercury slug in the uniform capillary glass tubing was found to work very well for a volume indicator. The changes in height of the mercury were measured with a cathetometer. An electric shaver was fastened on the metal support to the glass tubing to vibrate the tubing slightly, which greatly reduced friction between the glass and the mercury. To reduce the effect of friction further, by applying a slight pressure or vacuum to the top of the glass tube the mercury was made to approach the point of equilibrium from below and above, and an average of these readings was taken at each volume.

Procedure

Compression and decompression tests were run on a sample of Steven sand from the Paloma Field, Kern County, California, and on a sample of Berea sandstone from Berea, Ohio. The starting point for each run was 50 bars, since it was thought volume changes at lower pressure might not represent entirely changes in the pore volume of the sample. Pressure points were taken at 50, 100, 500, 750, and 1,000 bars at both increasing and decreasing pressure. A Bourdon gage was used to measure pressures. A hand pump made by American Instrument Company was used to apply pressure to the system. Kerosene was used as the pressure fluid.

EXPERIMENTAL RESULTS

Data and Graphs

Table I includes information on the sandstones upon which experimental tests were run. The origin of the sample, the bulk volume as determined by measurements of length and diameter, the pore volume as determined by a modified Boyle's Law apparatus, and the percent porosity (pore volume divided by bulk volume times one hundred) are given.

TABLE I
DESCRIPTION OF SAMPLES

Core No.	Sandstone	Origin	Run No.	Gross Volume	Pore Volume*	Percent Porosity*
195-B	Berea	Berea, Ohio	1	37.777	7.304	19.35
192	Steven	Kern Co., California	1	29.119	5.373	18.45
			2	29.034	5.288	18.21

* Values at beginning of run, i.e., 50 bars.

Table II includes the measured pore volumes of each of the samples at each pressure, the percent reduction in pore volume at each pressure, and the pressure coefficient of pore volume change for increasing pressures. The pore volume at each pressure was obtained from the distance which the mercury slug was displaced from its position at the same pressure at which the pore volume was originally determined by the Boyle's Law apparatus, using the cross-sectional area of the uniform capillary tubing (0.0208 cm^2) to convert this distance to volume. Thus, since the pore volume of each sample was previously measured at 500 bars pressure, the position of the mercury slug at 500 bars was taken as the zero mark from which all other volumes of the air in the core were determined. The percent reduction in pore volume calculated is the change in pore volume from that at 50 bars to the pore volume at each pressure, divided by the pore volume at 50 bars, multiplied by one hundred. The pressure coefficient of pore volume change at each pressure was found by drawing the best smooth curve through the points of Figures 1 and 2 and measuring its slope.

TABLE II
RESULTS OF MEASURING REDUCTION IN PORE VOLUME OF SANDSTONES

Core	Pressure (bars)	Pore Volume (cm^3)	Reduction in Pore Volume, Percent	Pressure Coef. of Pore Volume Change (1/bars)
195-B	50	7.304	0	7.94×10^{-6}
	100	7.290	0.19	7.94
	500	7.169	1.84	—
	750	7.126	2.49	4.82
	1,000	7.074	3.14	4.82
	750	7.122	2.49	—
	500	7.164	1.91	—
	100	7.277	0.36	—
	50	7.292	0.16	—
192 (Run 1)	50	5.373	—	38.58×10^{-6}
	100	5.323	0.93	25.86
	500	5.110	4.89	12.78
	750	5.035	6.29	8.82
	1,000	4.979	7.33	7.08
	750	5.009	6.77	—
	500	5.067	5.69	—
	100	5.236	2.54	—
	50	5.288	1.58	—
192 (Run 2)	50	5.288	0	21.36×10^{-6}
	100	5.259	0.55	19.92
	500	5.082	3.89	9.42
	750	5.023	5.01	7.74
	1,000	4.970	6.01	7.08
	750	5.001	5.42	—
	500	5.053	4.44	—
	100	5.247	0.77	—
	50	5.296	−0.15	—

Discussion of Results

Graphs of pore volume versus pressure are shown for each sample in Figures 1 and 2. It can be seen that the amount of hysteresis and permanent set observed in the run of the Berea sandstone in Figure 1 is very much less than that observed in the runs of the sample of Steven sand. In handling the two samples it was noted that the grains of the Berea sand seemed much more tightly cemented, and the core did not appear as friable as the Steven sand. It must be stated, also, that conditions of equilibrium were very difficult to obtain in the first run of the Steven sand. In fact, all the readings with increasing pressure above 50 bars were taken when the pore volume seemed to be decreasing very slowly, even as much as two hours after a higher pressure had been applied to the sample. This accounts in part for the larger hysteresis noted in Run 1 as compared to Run 2. No time lag was observed in Run 2 of the Steven sand or the run of the Berea sand. It would seem that such a long relaxation time is probably due to a rearrangement in position of grains in the sample, rather than to compression of grains or to further compression of the copper jacket. It seems unlikely that

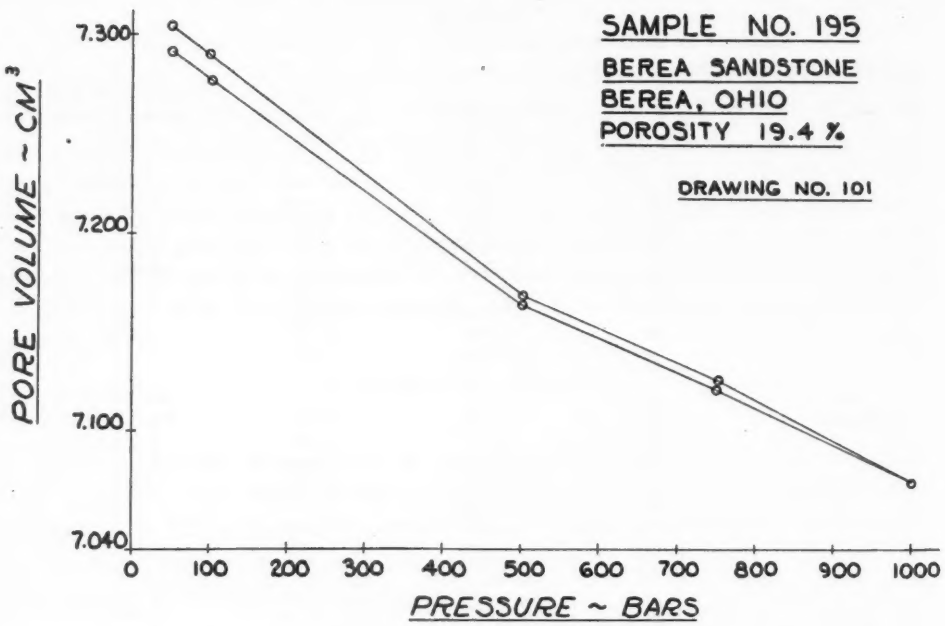

FIG. 1. Plot of pore volume versus pressure for Berea sandstone (sample 195).

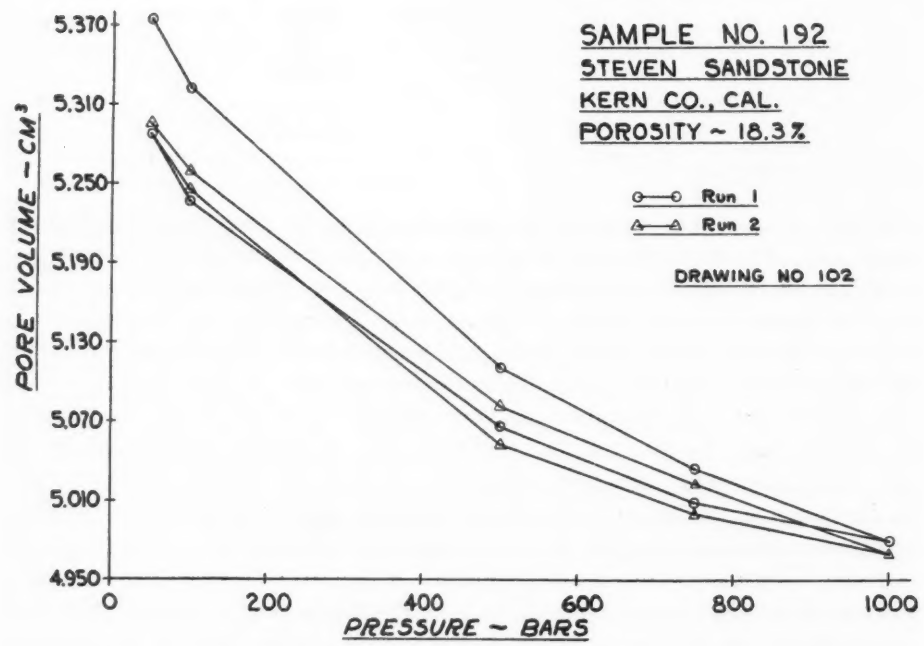

FIG. 2. Plot of pore volume versus pressure for Steven sandstone (sample 192).

the volume of the copper jacket could change so slowly at each pressure, or that the copper could be further imbedded into the pores of the sample at this stage. If the effect is due to a flow of solid material in the sample, then it must also have been occurring when pressure was applied to the sample before, and would have caused a permanent change in porosity. A permanent set amounting to about 1½ percent of the pore volume was noted in the first run of the Steven sand. Birch and Bancroft (1938), in measuring the velocity of waves in rocks by the resonant-frequency method, noted that " . . . after each change of pressure there is a period during which a small amount of after-working takes

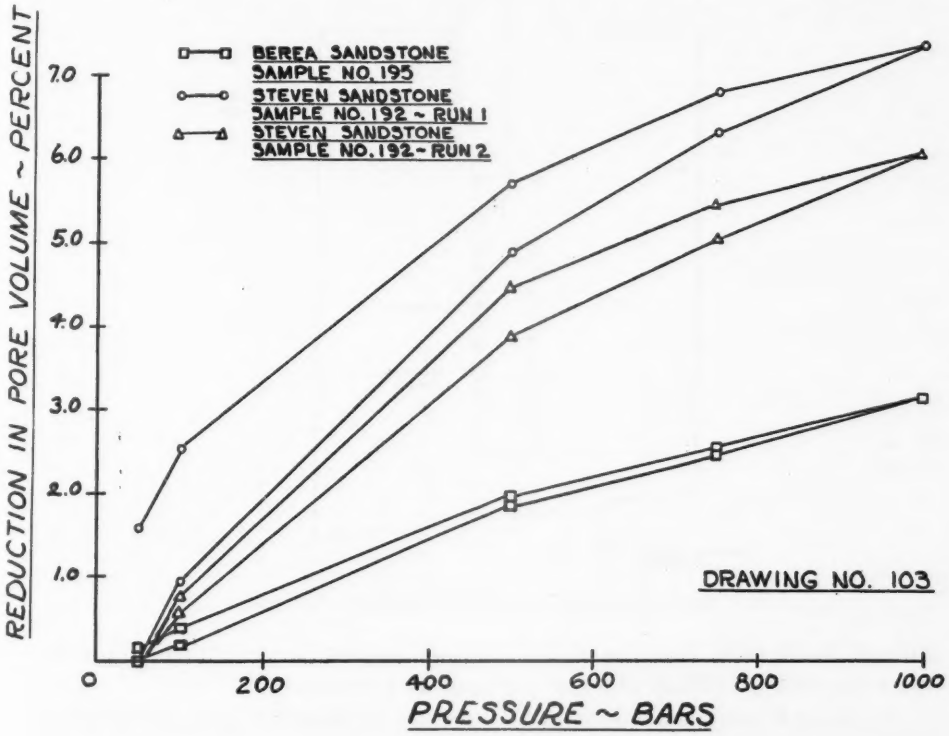

FIG. 3. Plot of percent change of pore volume at each pressure (samples 192 and 195).

place and the frequency increases a little more." Even though some of the permanent set noted in Run 1 of the Steven sand could be the effect of the jacket, there was surely some permanent set of the sample when pressure was applied to it before, in setting the copper jacket and in measuring porosity.

The total measured changes of pore volume correspond to a change from 19.35 percent to 18.84 percent in the porosity of the Berea sandstone, and from 18.45 percent to 17.31 percent in the porosity of the Steven sand. This would correspond to a change in the total available fluid capacity per acre-foot (1 acre-

foot equals the volume of a slab 1 foot thick and one acre in area) of the Berea sand of 213.4 cubic feet or 38 barrels, and of the Steven sand of 496.6 cubic feet or 88.5 barrels.

In Figure 3 is plotted the percent change of pore volume at each pressure. This would correspond to the percent change in volume available for containing fluids in a reservoir undergoing compaction. It can be seen that in all cases the larger part of the compaction occurs at low pressures. In the case of the first run of the Steven sand about two-thirds of the total amount of compaction takes place

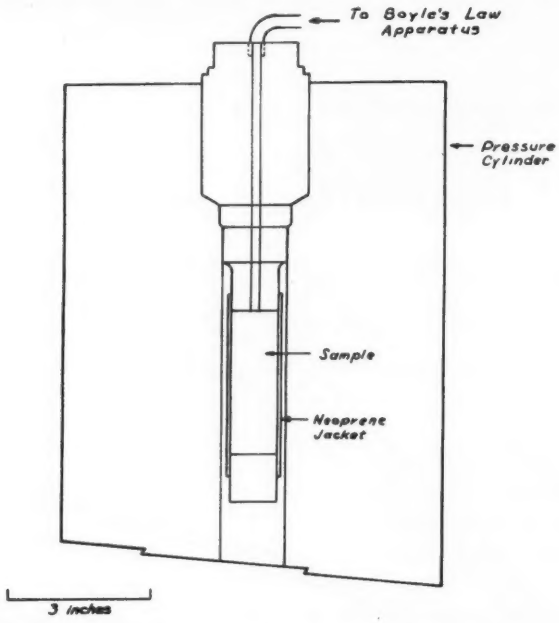

FIG. 4. Assembly for measuring porosity of samples.

from 50 to 500 bars. Thus the effect of compaction becomes much more important when the rock is initially at a low compressive pressure.

In Table II are given values for the pressure coefficient of pore volume change of the samples at increasing pressures computed from the slope of the pore volume curves at each pressure, this quantity being defined as,

$$R = -\frac{1}{V_p}\frac{dV_p}{dP}$$

where V_p = the pore volume of the sample, and P equals the pressure. The slope, dV_p/dP was obtained fairly accurately by using an adjustable angle triangle with a magnifying lens. The coefficient for the Berea sandstone cannot be established very accurately at each point due to the lack of points and the apparent small error in the data points. However, the order of absolute magnitude and

change can be obtained. In the case of the Steven sand, there is a continuously smooth change in values of the coefficient from 38.58×10^{-6} per bar at 50 bars to 7.08×10^{-6} per bar at 1,000 bars. It is interesting to note that the value at 1,000 bars is exactly the same in the first and second runs. The pressure coefficient of

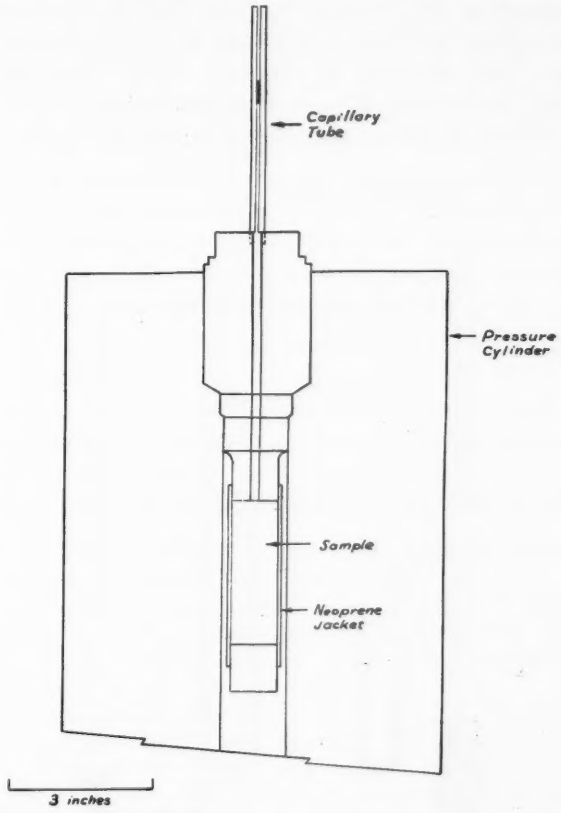

FIG. 5. Diagram of apparatus used for measuring changes in pore volume.

pore volume change of the Berea sand decreases from 7.94×10^{-6} to 4.82×10^{-6} per bar at 1,000 bars.

The maximum compressive pressure applied to the samples in these experiments is adequate to simulate pressure conditions existing in any producing oil reservoir. Assume, as is often done, that each foot of material overlying a reservoir contributes 1 pound per square inch to the pressure on the supporting material. The pressure tending to compress the rock is then, to a first approximation, the difference between the depth of the rock below the surface in feet and the fluid pressure in psi. Thus volume changes up to those expected to be produced by a drop in bottom-hole fluid pressure from 14,504 psi to 725 psi in a well at least 14,504 feet deep have been measured.

CONCLUSIONS

It appears that the change of pore volume with pressure of oil-bearing sandstones, although small, might be of significance in accurate reservoir calculations. If the initial differential between the geostatic pressure due to the overburden and the fluid pressure in the reservoir is small, that is, the pressure tending to compress the rock, then the effect of pressure on the sandstone when the fluid pressure decreases becomes more pronounced, since compressibility of sandstones is generally substantially greater at pressures below a few hundred bars. Porosity measurements made on sandstones in the laboratory are not apt to

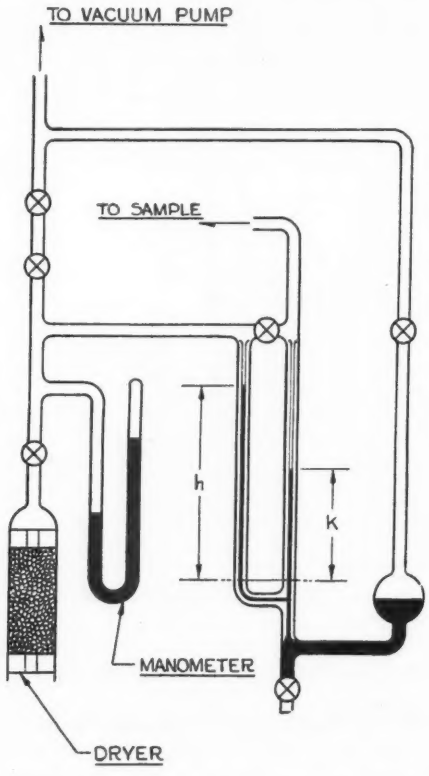

FIG. 6. Apparatus for measuring pore volumes by Boyle's law.

differ from the porosity of the sand in the reservoir by more than 2 porosity percent, so the difference would probably be of a little consequence in calibrating neutron logging instruments.

If it is assumed that the pore volume changes measured in these experiments are equal to the total change in bulk volume of the samples, i.e., the volume of solid material in the sample remains constant, then the quantity referred to as the pressure coefficient of pore volume change becomes identical to the com-

pressibility of the rock. The difference between these two quantities would be expected to be very small.

From these two samples it can be seen that wide differences exist in the amount of compaction which a consolidated sandstone may undergo when pressure is applied to its outside surfaces. A study of number and type of grain contacts in thin sections and of cementing materials of sandstone samples might enable one to make a fairly good estimate of the compressibility of a sample.

The experimental procedure required here of compressing the sample before measuring any pore volume changes probably results in making the changes measured smaller than if this procedure were not necessary, since a permanent set might occur in the sample. It seems likely that some loose-construction consolidated sandstones which have never been subjected to high pressures might exhibit a compression substantially greater than that measured on these samples. From the data taken here, a 7.3 percent reduction in pore volume of the Steven sandstone and a 3.2 percent reduction in pore volume of the Berea sandstone were calculated when the compressing pressure was changed from 50 to 1,000 bars.

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STRAIN-WAVE SHAPES IN ROCK NEAR EXPLOSIONS*

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ABSTRACT

The shapes of displacement, velocity, acceleration and strain-wave pulses in solid elastic media near a spherical cavity in which the applied pressure pulse is of the general form

$$p = p_0[e^{-\alpha t} - e^{-\beta t}]$$

have been calculated. The computed strain-wave pulse shapes at various distances from the cavity are compared with typical experimentally recorded strain-wave pulses and are shown to have similar characteristics. The shapes of the wave pulses, that is, the rise time, pulse width, etc., are shown to be functions of the applied pressure pulse, the distance from the cavity and the properties of the solid medium.

During the past several years the Applied Physics Branch has studied the generation and propagation of strain waves in rock produced by the detonation of high-velocity explosives placed in small cavities in the rock.[1,2,3,4] The strain waves were recorded by means of strain gages mounted in the solid rock surrounding the explosive charge. Hundreds of radial strain-wave pulses have been recorded in different rock types for charges of various sizes and at various distances from the charge.

Analysis of these records has shown, among other things, that, as the distance between the charge and gage decreases, the oscillatory nature of the radial strain wave pulse diminishes. For relatively short distances between charge and gage, the radial strain-wave pulse is nonoscillatory in nature, having only a compressive strain cycle that decreases slowly to zero. A possible explanation of the above results could be that close to the charge the rock is in a nonelastic state. However, it will be shown in the following that the above observed phenomena of nonoscillatory strain wave pulses may occur for a perfect elastic medium when the distance from the cavity is small and the applied pressure pulse is long compared to the period of the cavity.

Sharpe[5] has determined theoretically the wave motion resulting from the ap-

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plication of a pressure pulse to the interior surface of a spherical cavity in a solid medium. His solution is based upon the assumptions that the medium is perfectly elastic, that Poisson's ratio is 0.25, and that the pressure is applied normal to the spherical surface. His equation for the displacement potential resulting from the application of a pressure pulse of the form[6]

$$p = p_0 e^{-\alpha t} \tag{1}$$

is

$$\Phi = \frac{a p_0/\rho r}{\left(\frac{\omega}{\sqrt{2}} - \alpha\right)^2 + \omega^2} \left\{ -e^{-\alpha\tau} + e^{-\omega\tau/\sqrt{2}} \left[\left(\frac{1}{\sqrt{2}} - \frac{\alpha}{\omega} \right) \sin \omega\tau + \cos \omega\tau \right] \right\}, \tag{2}$$

where

$$\omega = \frac{2\sqrt{2}c}{3a}, \tag{3}$$

$$\tau = t - \frac{r - a}{c}, \tag{4}$$

$$c = \sqrt{\frac{3\mu}{\rho}}. \tag{5}$$

For an applied pressure of the form

$$p = -p_0 e^{-\beta t}, \tag{6}$$

the displacement potential would be the same as equation 2, except $-p_0$ would replace p_0 and β would replace α. By the method of superposition the displacement potential resulting from application of a pressure pulse of the form

$$p = p_0 (e^{-\alpha t} - e^{-\beta t}) \tag{7}$$

would be given by

$$\Phi = \frac{a p_0/\rho r}{\left(\frac{\omega}{\sqrt{2}} - \alpha\right)^2 + \omega^2} \left\{ -e^{-\alpha\tau} + e^{-\omega\tau/\sqrt{2}} \left[\left(\frac{1}{\sqrt{2}} - \frac{\alpha}{\omega} \right) \sin \omega\tau + \cos \omega\tau \right] \right\}$$

$$+ \frac{a p_0/\rho r}{\left(\frac{\omega}{\sqrt{2}} - \beta\right)^2 + \omega^2} \left\{ +e^{-\beta\tau} - e^{-\omega\tau/\sqrt{2}} \left[\left(\frac{1}{\sqrt{2}} - \frac{\beta}{\omega} \right) \sin \omega\tau + \cos \omega\tau \right] \right\}. \tag{8}$$

From equation (8) the particle displacement, u; particle velocity, v; particle

[6] A list of symbols is given in appendix I.

acceleration, A; radial strain, ϵ; and dilatation, Δ; can be derived by the following:

$$u = \frac{\partial \Phi}{\partial r}, \tag{9}$$

$$v = \frac{\partial u}{\partial t}, \tag{10}$$

$$A = \frac{\partial v}{\partial t}, \tag{11}$$

$$\epsilon = \frac{\partial u}{\partial r}, \tag{12}$$

$$\Delta = \frac{\partial u}{\partial r} + 2\frac{u}{r}. \tag{13}$$

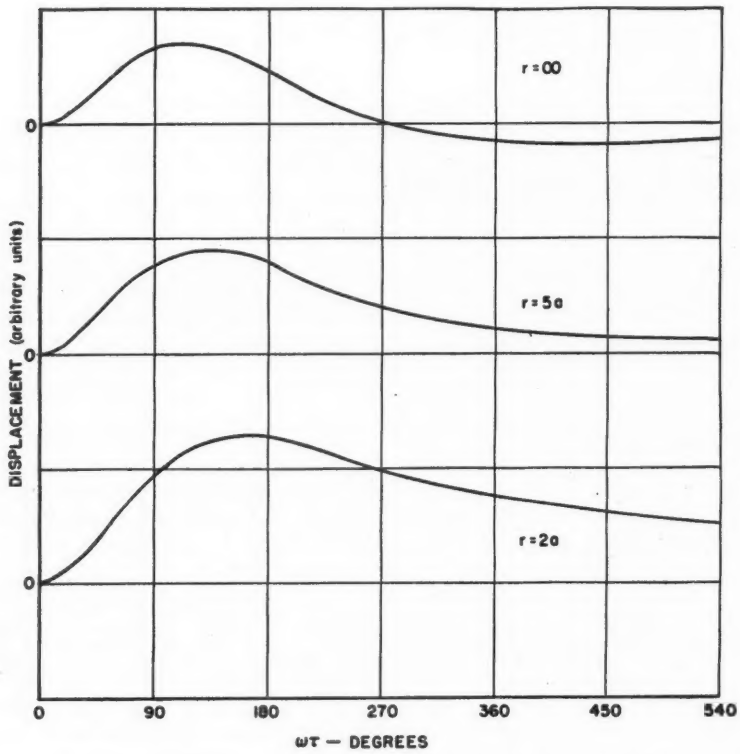

FIG. 1. Shape of displacement wave pulses for pressure

$$p = p_0(e^{-\omega t/4\sqrt{2}} - e^{-\omega t/2\sqrt{2}}).$$

These derivations have been carried out and the final equations are given in Appendix II. If all terms are retained in these equations, the results are valid from the radius of the cavity to infinity. Examination of these equations shows that the shapes of the displacement, velocity, acceleration and strain-wave pulses are functions of both the applied pressure pulse and the distance from the cavity. The shape of the dilatation wave pulse is a function of the applied pressure pulse b t is independent of the distance from the cavity and has the same shape as the radial strain pulse at infinity. The shapes of the different wave pulses at different distances from the cavity have been computed from the equations given in Appendix II.

Figures 1, 2, 3, and 4 show the shapes of the displacement, velocity, acceleration, and strain-wave pulses at distances from the cavity of 2a, 5a, and ∞, for an applied pressure pulse of the form

$$p = p_0[e^{-\omega t/4\sqrt{2}} - e^{-\omega t/2\sqrt{2}}]. \tag{14}$$

Examination of these wave pulses shows that, as the distance from the cavity

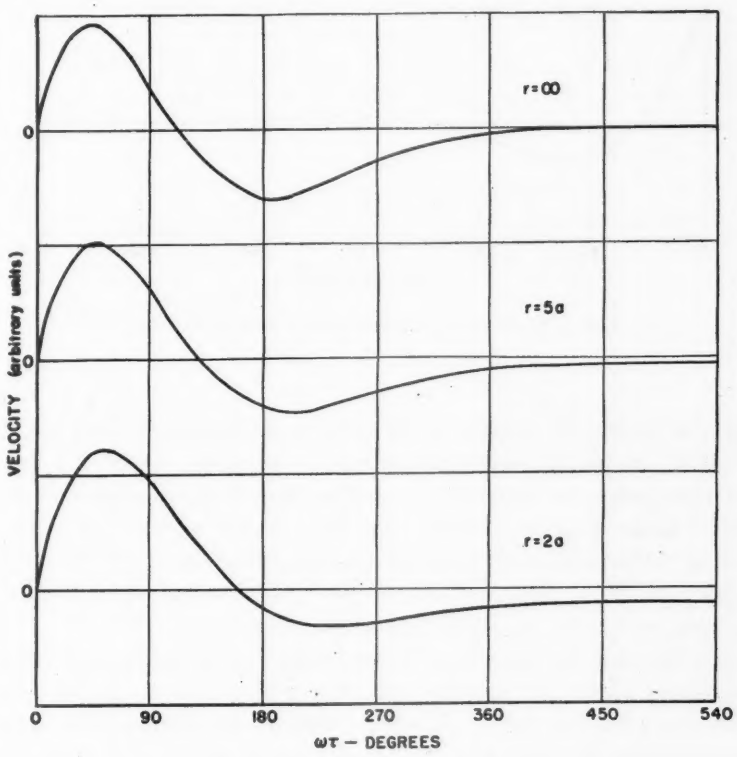

FIG. 2. Shape of velocity wave pulses for pressure

$$p = p_0(e^{-\omega t/4\sqrt{2}} - e^{-\omega t/2\sqrt{2}}).$$

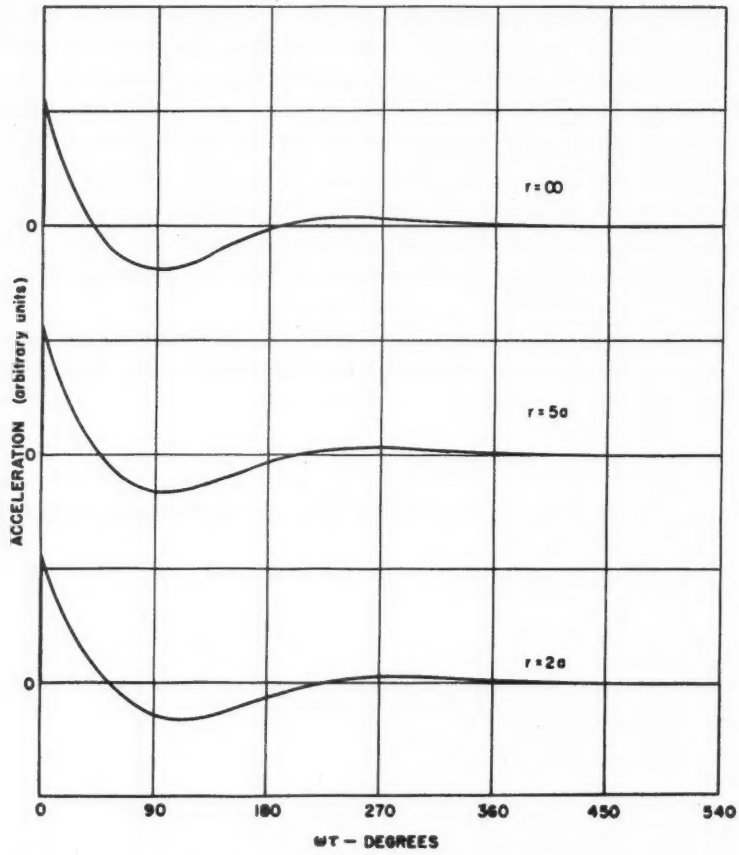

FIG. 3. Shape of acceleration wave pulses for pressure

$$p = p_0(e^{-\omega t/4\sqrt{2}} - e^{-\omega t 2\sqrt{2}}).$$

decreases, the oscillatory nature of the wave pulse decreases. This effect is most pronounced in the displacement and strain-wave pulses, where, for distances of $2a$, these wave pulses are entirely in one direction. Further examination of these wave shapes shows that the elapsed time between the start of the pulse and the first crossing of the base line is not a half period of the frequency of the wave pulse as given by equation 3. Rather it determines a pulse width which is a function of distance from the cavity for a given pressure pulse.

Figure 5 shows three types of pressure pulses drawn to the same time scale as the wave pulses. The upper pressure pulse was used in computing the wave shapes in Figures 1, 2, 3, and 4. The two lower pressure pulses were used to compute the strain-wave pulses shown in Figures 6 and 7. Comparison of Figures 4, 6, and 7 shows that, as the length of the pressure pulse increases, the strain-wave pulse

length increases; also, the nonoscillatory nature of strain-wave pulses is more pronounced at close distances for the longer pressure pulses. Thus, the pulse length of the strain wave is a function of both the distance from the cavity and the shape of the applied pressure pulse.

By considering the relative amplitudes of the peak strains at various distances from the cavity, an average propagation law for the decrease of peak strain with distance close to the shot point was determined as

$$\epsilon = \frac{k}{r^{1.5}}. \tag{15}$$

From experimental field data, the exponent of r has been found to range in value from 1.6 to 2.5 for various rock types and explosives. The higher value of

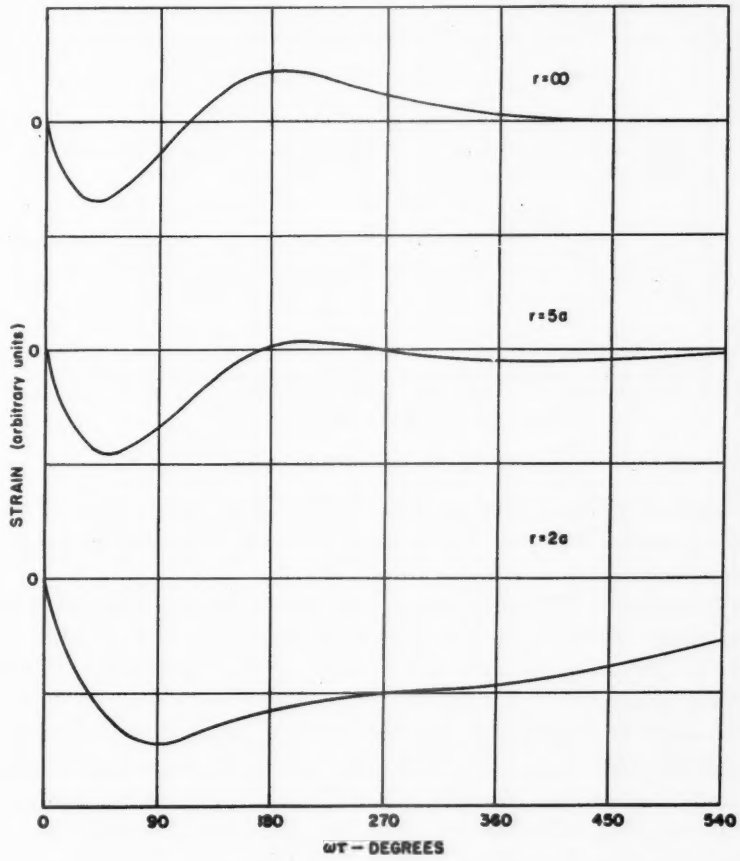

FIG. 4. Shape of strain wave pulses for pressure

$$p = p_0(e^{-\omega t/4\sqrt{2}} - e^{-\omega t/2\sqrt{2}}).$$

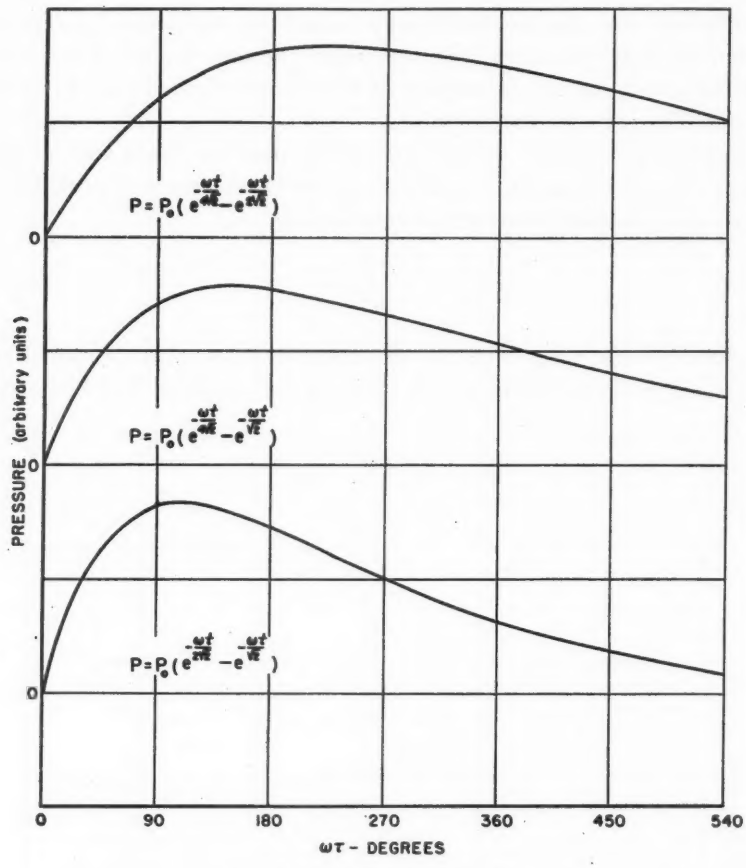

FIG. 5. Shape of pressure pulses.

the experimentally determined exponent would be expected because absorption of energy by the rock has not been taken into account in the above theoretical discussion.

Several examples of typical strain-wave pulses recorded in shale and sandstone for charge sizes of $\frac{3}{4}$, 6, and 12 pounds are shown in Figures 8, 9, and 10, respectively. Inspection of these records shows that, in general, the shapes of these strain-wave pulses are similar to those theoretically derived. The following observations can be noted. First, for short travel distances the strain pulse is usually a single pulse of compressive strain; also this phenomenon is more pronounced for the larger charge sizes. Second, as the distance from the charge increases the strain pulse takes on an oscillatory character that increases with travel distance. Third, the pulse length decreases with distance for short distances and increases with distance for large distances. The increase in pulse length with large travel distance is most likely a result of absorption in the rock that has not been taken into account in the above theory.

Examples of typical strain-wave pulses recorded in granite are shown in Figures 11 and 12. These records are given to illustrate how the type and rate of detonation of the explosive charge affects the shape of the pressure pulse applied to the cavity, which in turn affects the shape of the strain-wave pulse. Unfortunately the charge size is not the same for these two sets of records; therefore, direct comparison is not possible. However, the following observations can be made from these two sets of records. First, the rise time of the strain-wave pulse is faster for the higher-rate explosive. Second, the nonoscillatory character of the strain-wave pulse close to the charge is more pronounced for the slower-rate explosive, even though the charge size for the slower-rate explosive was smaller than the higher-rate explosive. Third, at large distances the pulse lengths of the strain pulses in granite are shorter than those observed in either sandstone or shale.

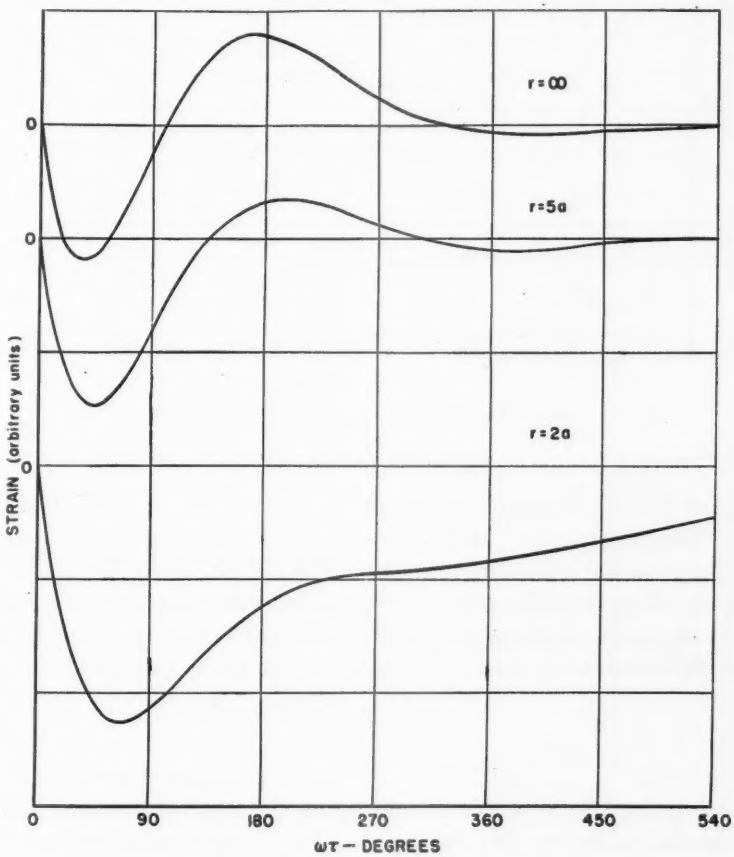

FIG. 6. Shape of strain wave pulses for pressure

$= p_0(e^{-\omega t/4\sqrt{3}} - e^{-\omega t/\sqrt{3}})$.

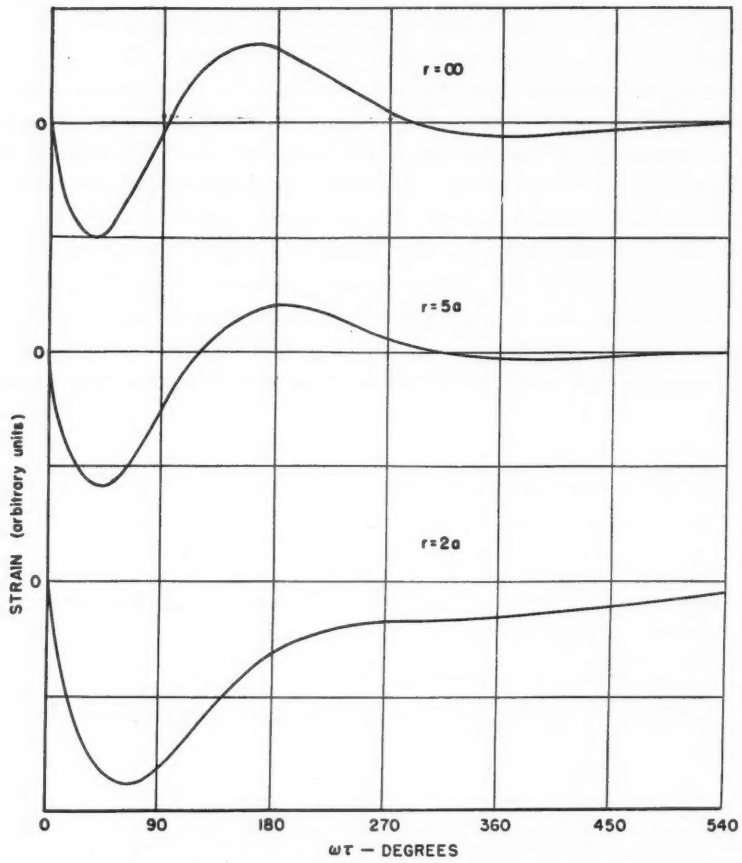

FIG. 7. Shape of strain wave pulses for pressure

$$p = p_0(e^{-\omega t/2\sqrt{2}} - e^{-\omega t/\sqrt{2}}).$$

The principal conclusions that can be drawn from the above results are given below. (1) The occurrence of nonoscillatory strain-wave pulses near an explosion cannot be used to determine directly the limit of elastic behavior in the rock surrounding the charge. (2) The pulse width, as determined by measuring the elapse time from the start of the strain pulse to the next crossing of the base line, is not a half period of the frequency, as given by Sharpe's equation

$$\omega = \frac{2\sqrt{2}c}{3a}. \tag{16}$$

Instead the pulse length is also a function of the applied pressure and the distance from the cavity. (3) The shape of the strain-wave pulse is a function of the rock type, the applied pressure pulse, and the distance from the cavity. Some of the effects produced in the strain-wave pulse by changing the rock type and the

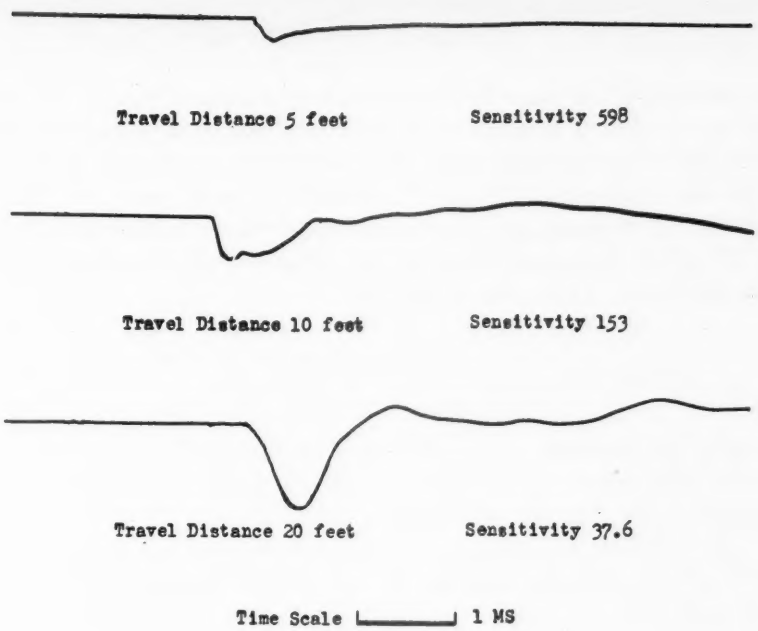

FIG. 8. Typical strain records for Pierre shale.

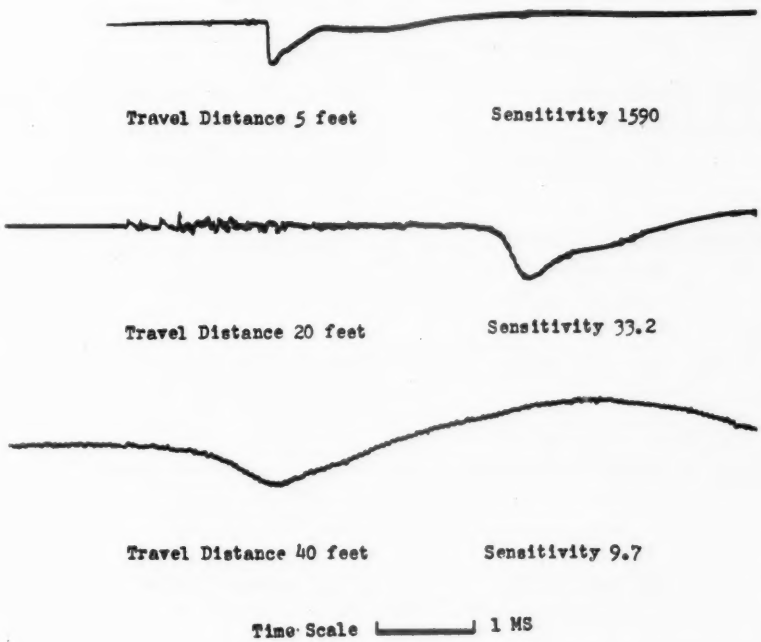

FIG. 9. Typical strain records for Homewood sandstone.

applied pressure pulse have been observed experimentally. (4) For distances close to the charge the average decrease of peak strain with distance should be approximately $r^{-1.5}$. Experimentally the observed decay of peak strain with distance has been between $r^{-1.6}$ to $r^{-2.5}$ for different rock types and different explosives. (5) The shape of the dilatation pulse is independent of distance from the cavity. Therefore this quantity should be measured when attempting to determine the absorption properties of the rock.

APPENDIX I

List of Symbols

A = Particle Acceleration
a = Radius of Cavity
c = Propagational Velocity of Longitudinal Wave
e = Base of the Natural System of Logarithms
m = Constant
n = Constant
p = Variable Pressure
p_0 = Constant Pressure
r = Radial Distance from Center of Cavity
t = Time
u = Particle Displacement
v = Particle Velocity
α = Constant
β = Constant
Δ = Dilatation
ϵ = Radial Strain
θ_1 = Phase Angle
θ_2 = Phase Angle
θ_3 = Phase Angle
μ = Modulus of Rigidity
ρ = Density
τ = Time
Φ = Displacement Potential Function
ω = Angular Frequency

APPENDIX II

From equation 8 and the following five relations

$$\alpha = n\omega/\sqrt{2}, \tag{17}$$

$$\beta = m\omega/\sqrt{2}, \tag{18}$$

$$\theta_1 = \tan^{-1}\frac{\sqrt{2}}{1-n}, \tag{19}$$

$$\theta_2 = \tan^{-1}\frac{\sqrt{2}}{1-m}, \tag{20}$$

$$\theta_3 = \tan^{-1}\sqrt{2}, \tag{21}$$

the particle displacement, particle velocity, particle acceleration, radial strain, and dilatation have been derived and are given as follows.

Travel Distance 5 feet Sensitivity 3000

Travel Distance 20 feet Sensitivity 65.5

Travel Distance 40 feet Sensitivity 15.5

Time Scale ⌊——⌋ 1 MS

Explosive, 12 lbs. 60% Ammonia Gelatin

FIG. 10. Typical strain records for Homewood sandstone.

Travel Distance 5 feet Sensitivity 1610

Travel Distance 20 feet Sensitivity 405

Travel Distance 40 feet Sensitivity 208

Time Scale ⌊—⌋ 1 MS

Explosive, 22.8 lbs. 80% Hi-Velocity Gelatin
Detonation Rate 21,600 ft/sec

FIG. 11. Typical strain records for Lithonia granite.

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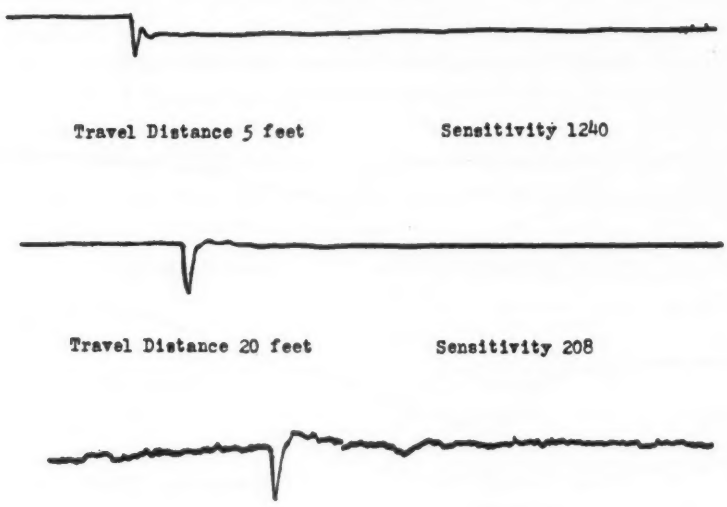

FIG. 12. Typical strain records for Lithonia granite.

$$u = \frac{9ap_0}{4\rho c^2}\left(\frac{a}{r}\right)\left\{\left(\frac{a}{r} - \frac{2n}{3}\right)\frac{e^{-n\omega\tau/\sqrt{2}}}{3 - 2n + n^2} - \left(\frac{a}{r} - \frac{2m}{3}\right)\frac{e^{-m\omega\tau/\sqrt{2}}}{3 - 2m + m^2}\right.$$
$$- \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2n + n^2}}\left[\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_1) - \frac{2\sqrt{3}}{3}\sin(\omega\tau + \theta_1 - \theta_3)\right]$$
$$+ \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2m + m^2}}\left[\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_2)\right.$$
$$\left.\left. - \frac{2\sqrt{3}}{3}\sin(\omega\tau + \theta_2 - \theta_3)\right)\right]. \qquad (22)$$

$$v = \frac{3p_0}{2\rho c}\left(\frac{a}{r}\right)\left\{-n\left(\frac{a}{r} - \frac{2n}{3}\right)\frac{e^{-n\omega\tau/\sqrt{2}}}{3 - 2n + n^2} + m\left(\frac{a}{r} - \frac{2m}{3}\right)\frac{e^{-m\omega\tau/\sqrt{2}}}{3 - 2m + m^2}\right.$$
$$+ \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2n + n^2}}\left[\sqrt{3}\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_1 - \theta_3)\right.$$
$$\left.\left. - 2\sin(\omega\tau + \theta_1 - 2\theta_3)\right]\right.$$

$$- \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2m + m^2}}\left[\sqrt{3}\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_2 - \theta_3) - 2\sin(\omega\tau + \theta_2 - 2\theta_3)\right]\Bigg\} \quad (23)$$

$$A = \frac{p_0}{\rho a}\left(\frac{a}{r}\right)\Bigg\{n^2\left(\frac{a}{r} - \frac{2n}{3}\right)\frac{e^{-n\omega\tau/\sqrt{2}}}{3 - 2n + n^2} - m^2\left(\frac{a}{r} - \frac{2m}{3}\right)\frac{e^{-m\omega\tau/\sqrt{2}}}{3 - 2m + m^2}$$
$$- \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2n + n^2}}\left[3\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_1 - 2\theta_3) - 2\sqrt{3}\sin(\omega\tau + \theta_1 - 3\theta_3)\right]$$
$$+ \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2m + m^2}}\left[3\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_2 - 2\theta_3) - 2\sqrt{3}\sin(\omega\tau + \theta_2 - 3\theta_3)\right]\Bigg\}. \quad (24)$$

$$\epsilon_r = \frac{9p_0}{4\rho c^2}\left(\frac{a}{r}\right)\Bigg\{-\left[2\left(\frac{a}{r}\right)^2 - \frac{4n}{3}\frac{a}{r} + \frac{4n^2}{9}\right]\frac{e^{-n\omega\tau/\sqrt{2}}}{3 - 2n + n^2}$$
$$+ \left[2\left(\frac{a}{r}\right)^2 - \frac{4m}{3}\frac{a}{r} + \frac{4m^2}{9}\right]\frac{e^{-m\omega\tau/\sqrt{2}}}{3 - 2m + m^2}$$
$$+ \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2n + n^2}}\left[2\left(\frac{a}{r}\right)^2\sin(\omega\tau + \theta_1) - \frac{4\sqrt{3}}{3}\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_1 - \theta_3) + \frac{4}{3}\sin(\omega\tau + \theta_1 - 2\theta_3)\right]$$
$$- \frac{e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2m + m^2}}\left[2\left(\frac{a}{r}\right)^2\sin(\omega\tau + \theta_2) - \frac{4\sqrt{3}}{3}\left(\frac{a}{r}\right)\sin(\omega\tau + \theta_2 - \theta_3) + \frac{4}{3}\sin(\omega\tau + \theta_2 - 2\theta_3)\right]\Bigg\}. \quad (25)$$

$$\Delta = \frac{p_0}{\rho c^2}\left(\frac{a}{r}\right)\Bigg[-n^2\frac{e^{-n\omega\tau/\sqrt{2}}}{3 - 2n + n^2} + m^2\frac{e^{-m\omega\tau/\sqrt{2}}}{3 - 2m + m^2}$$
$$+ \frac{3e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2n + n^2}}\sin(\omega\tau + \theta_1 - 2\theta_3)$$
$$- \frac{3e^{-\omega\tau/\sqrt{2}}}{\sqrt{2}\sqrt{3 - 2m + m^2}}\sin(\omega\tau + \theta_2 - 2\theta_3)\Bigg]. \quad (26)$$

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CORE HOLE VELOCITY SURVEYS*

J. B. H. HENDERSON† AND R. BREWER††

ABSTRACT

A method for conducting velocity surveys in exploratory core holes has been developed. A gun perforator is used in connection with electric logging equipment. Below fifty feet, errors are small. Results are satisfactory in programs described in north Louisiana, south Arkansas, and North Dakota.

Origin of the present movement for more and better velocity control can be traced back to the begnning of the seismic method. Compared with a now velocity conscious industry, the early days saw only a small group who concerned themselves with the effects of velocities, near surface or otherwise. As long as the objects of seismic search were large anticlinal structures, errors in velocity assumptions were only of academic importance. Since then the situation has changed, particularly in the older provinces where most of the major structures already have been found. In many instances now a structure with one hundred feet of closure or perhaps even less may be considered a drillable prospect, provided, of course, it can be assigned a reasonably high seismic reliability factor. To find and map with accuracy a structure of that order requires that most of the factors responsible for errors be ascertained and held in check.

Recent years have seen the development of a velocity measuring technique that may one day make velocity surveys possible in far more wells than now are surveyed. This system has been described in the literature, and results obtained through its use have been discussed in papers presented at several exploration meetings. To summarize briefly, a standard gun perforator with selective firing is lowered into the bore hole as the energy source, and seismometers or groups of seismometers are placed at the surface, usually at several distances from the hole. Up to forty shots can be fired before the gun must be reloaded; therefore, this system is much faster than the conventional method which requires that charges be loaded individually in shot holes. Elimination of the shot holes themselves represents another important advantage.

By acquiring velocity data in all structure holes or core holes and supplementing it with velocity data taken in stratigraphic tests and wells, a gradual accumulation of such data can be effected and used should an area later develop interest from a seismic standpoint. There are numerous cases in which the data are immediately useful as is the case when a structure drill or core drill is used for reconnaissance work. An anomaly having thus been found, it is the practice

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of many companies to check the deeper horizons by seismograph. Core hole velocity data in some cases permits refinement of the seismic computations. Conversely, areas have been shot with results that were not easily interpreted and later they were core drilled. The results of the velocity surveys may permit re-interpretation of the seismic data.

Some months ago experiments for running velocity surveys in exploratory core holes were initiated to examine the practicability of using the gun perforator, in connection with electric logging equipment already in use. Those experiments were attended with such success that velocity surveys now are offered as part of the standard core drill service at only a moderate additional cost.

Seismic equipment requirements are relatively simple, but the amplifier specifications differ somewhat from those for conventional seismic applications. Gain requirements are similar but filter and automatic gain control problems are not as severe. In fact, in most velocity survey applications automatic gain control is not desirable, and it has been omitted entirely in the amplifiers described here.

In this application, four recording channels are used with a single seismometer per trace. The four amplifiers are constructed in a single compact unit. Each amplifier uses four resistance-coupled, high-gain triode stages with transformer coupling on both input and output. Gain is adjustable in 6db steps for a

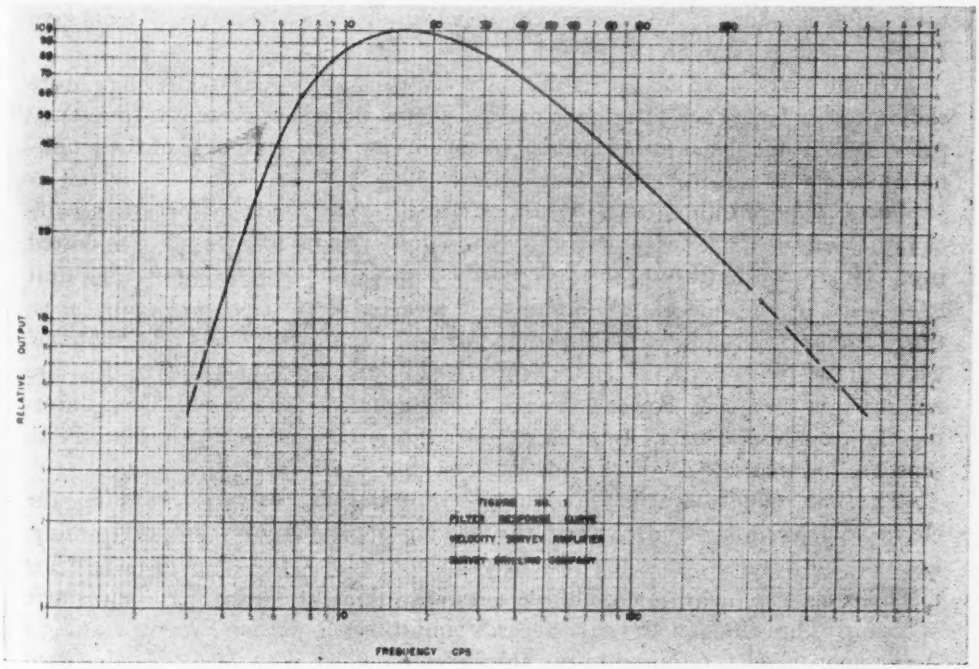

FIG. 1. Filter response of the amplifier.

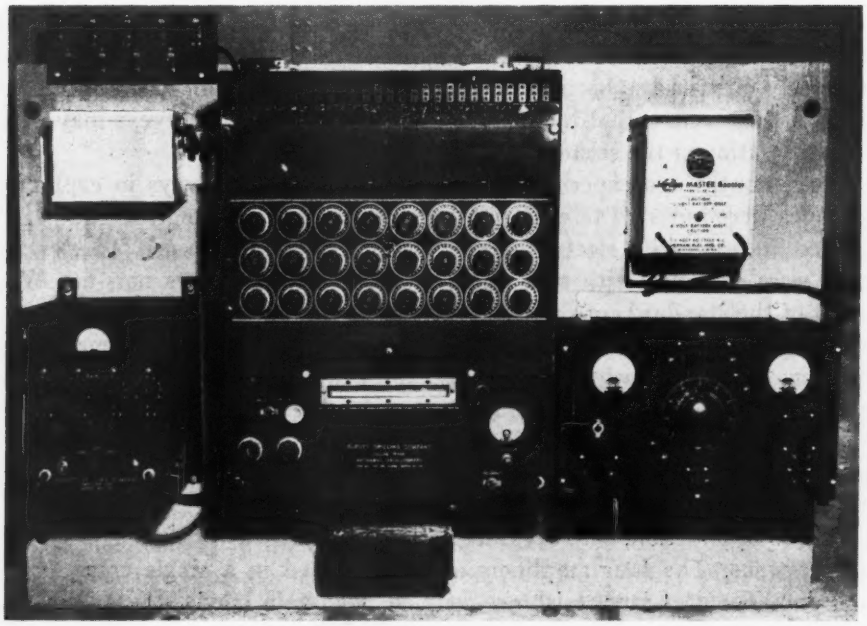

FIG. 2. Instrument arrangement.

total range of 48db, and at the maximum position 1 microvolt input signal give $\frac{3}{4}$ inch trace deflection on the record.

A band pass of 10–60 cps is obtained by resistor-capacitor filtering. More elaborate low frequency filtering is not considered necessary since low frequency problems are not encountered in this type of survey. Filter response of the amplifier is shown in Figure 1.

Power required for the four channels is small. One-hundred thirty-five volts of radio type B batteries supply the high voltage, while filaments are operated from the storage battery used to supply power for the camera lamps. The unit is enclosed in an anodized aluminum case measuring $8\frac{1}{8}'' \times 10'' \times 7\frac{1}{2}''$. All tubes, transformers, and other electrical components are mounted on a single subpanel while the switches and the meters for the test unit and the gain controls are mounted on the panel. Power connections are made through flexible leads entering the unit at the back. Input and output connections are made directly to separate terminal blocks or clip boards.

The instruments are mounted in the recording truck, which contains the electrical logging equipment; and the logging engineer, with proper training, can take both the electrical log and the velocity survey. The gun perforator firing mechanism is mounted alongside the seismic equipment, which permits a single operator to fire the gun and take records simultaneously. (See Figures 2 and 3.) A winch operator is required to run the winch on which is spooled the cable used for logging and for firing the gun perforator. Because this operator is a member

of the drilling crew, the necessity for additional personnel is thus eliminated. The entire instrument mounts on a shock-mounted instrument board.

A conventional test unit, providing leakage, continuity, and similarity checks, is an integral part of the instrument. This gives maximum flexibility in operation yet enables the observer to check completely the four recording channels prior to a survey.

A standard Hathaway oscillograph using 4-inch recording paper completes the recording system.

For core holes, eight and twenty-four shot Schlumberger gun perforators have been employed. Each charge consists of 11½ to 12 grams of oval powder, a little less than four times the charge in an ordinary twelve-gauge shotgun shell. Figure 4 shows one of the guns loaded and ready to be lowered into a hole.

Figure 5 shows a group of records taken in Columbia County, Arkansas. This group is representative of the area, and it will be noted that without exception the breaks are clean. At no time was it necessary to increase amplifier sensitivity beyond the 30db step, nor was it necessary to use more than one seismometer per trace.

Data from the records in Figure 5 are plotted on the velocity curves of Figure 5-a. Seismometers were placed at distances of 20, 30, 40, and 90 feet and, in order to examine the data individually, the 30, 40, and 90 foot plots have been

FIG. 3. Instrument cab.

FIG. 4. Gun perforator.

displaced .010, .020, and .030 second, respectively. The curves show good agreement.

It will be noted in the foregoing illustration that observed times have been plotted against slant distance from shot to seismometer. There are those who prefer to use vertical distances and to correct observed times accordingly through use of a cosine factor. The authors feel that either method is acceptable and the slant distance system has been used in this work purely for reasons of expediency. There being four curves to plot for each core hole, it is simpler and faster to read slant distances from a table rather than to correct each observed time with a different factor. At the shallower depths, say above fifty feet, there admittedly in some error but it should be pointed out that the principal objective of this core drill velocity work has been to explore velocity conditions below that depth; and below fifty feet the errors are small.

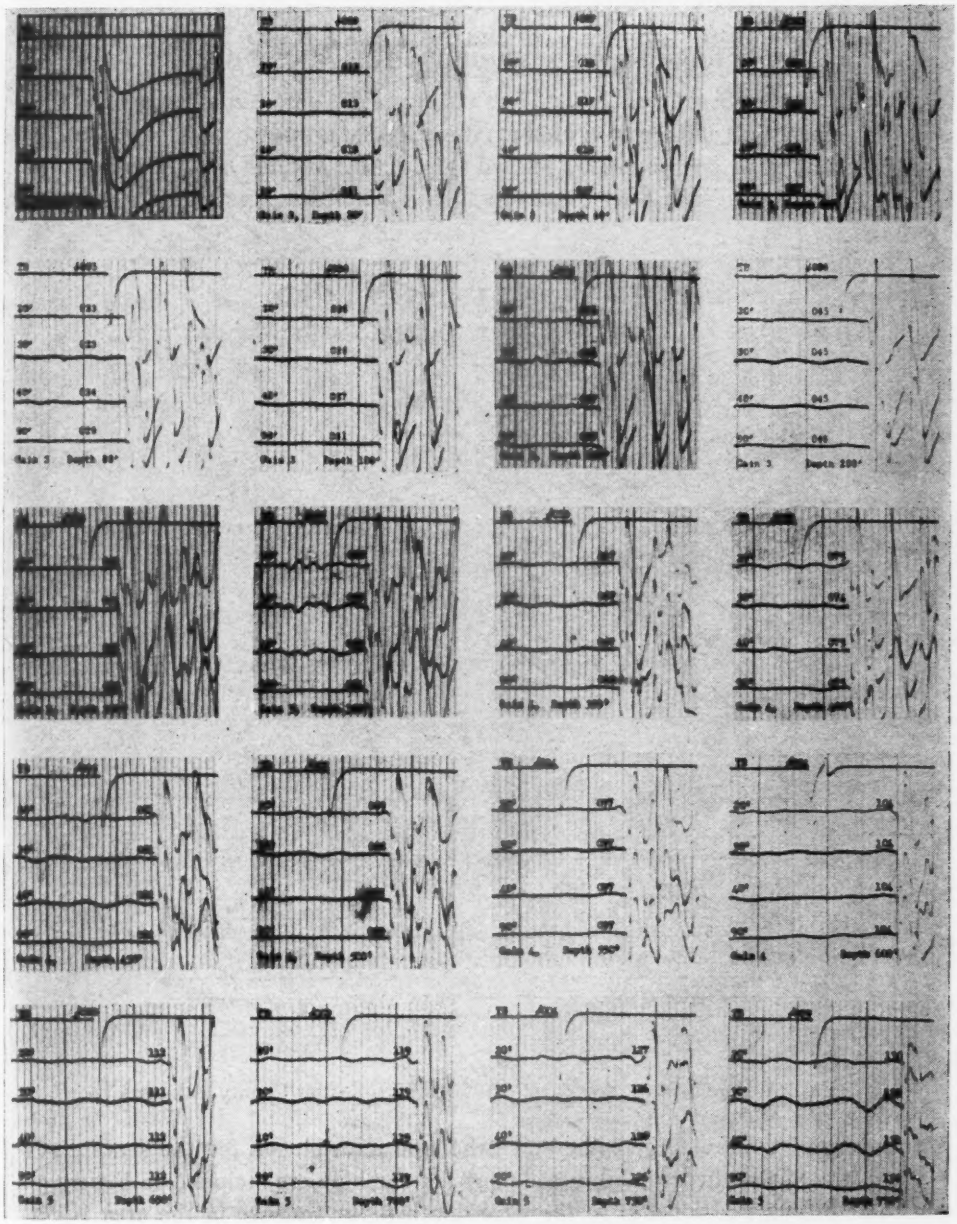

FIG. 5. Core Hole 83, Section 34, T16S-R20W, West Magnolia Area, Columbia County, Arkansas.

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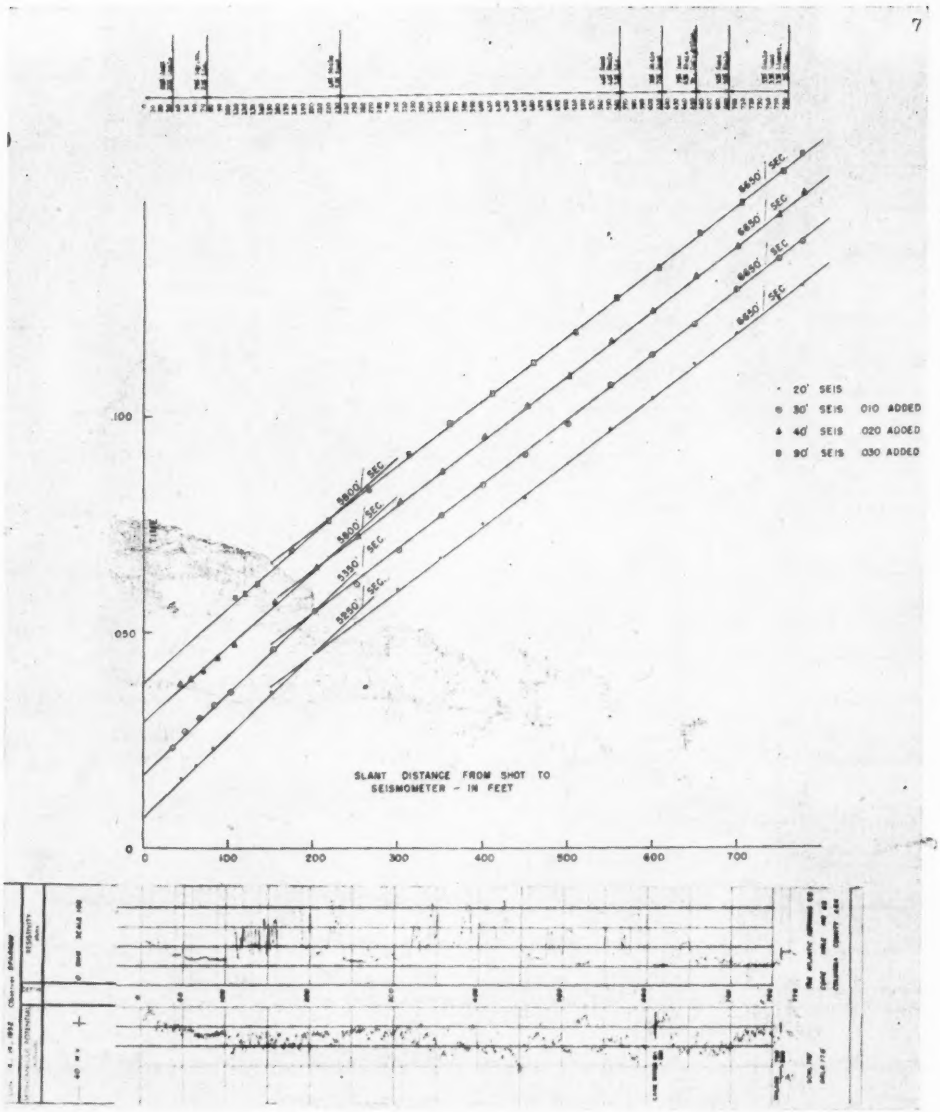

FIG. 5A. Core Hole 83, Section 34, T16S-R20W, Columbia County, Arkansas.

In order to provide geologic and lithologic information for the section surveyed, the Schlumberger and sample logs for the hole are included in Figure 5-a in their proper relationship to the time-depth plots. Surface in the area is generally composed of quaternary gravels with outcrops of Claiborne. The creek and river bottoms contain recent alluvium. All of the holes were drilled in undifferentiated Claiborne which consisted mainly of intermittent sands and shales with occasional streaks of lignite.

At the outset of the program some trouble was anticipated from cable breaks, particularly on the closer seismometers, but that trouble failed to materialize to any great degree. Out of some fifty core holes surveyed in Columbia and Lafayette Counties, Arkansas, only three gave any trouble at all. Velocity curves for one of the troublesome holes appears in Figure 6, but it will be seen there that only the 10 and 20 foot traces are affected. It is probable that there, as well as in the other two holes in which cable breaks were observed, the gun perforator or cable was resting against the side of the hole. That difficulty has been com-

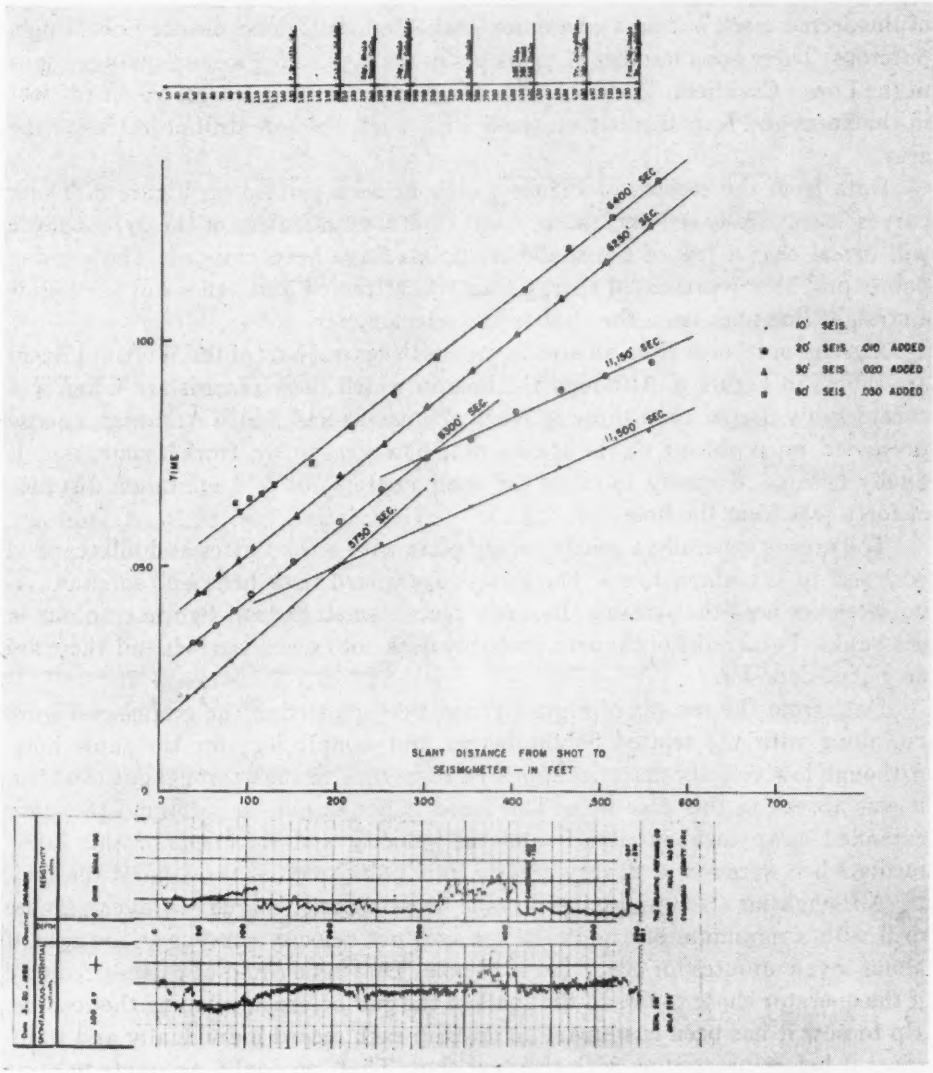

FIG. 6. Core Hole 63, Section 1, T18S-R23W, Columbia County, Arkansas.

pletely eliminated in subsequent work simply by using a rag as an acoustical insulator to center the cable in the hole.

In Figure 7 may be seen a set of records from a core hole in Jackson Parish, Louisiana. This area was slightly less sensitive than Columbia County, and it was necessary to operate the gain a little higher, particularly on the deeper shots. Breaks were excellent, however, and records shown there are about average for the area.

Surface of the area is comprised of residual sands of the Eocene Cockfield. The sand is thickest, up to 120 feet, on the hills; and it is entirely absent in some of the deeper creek bottoms where the Cook Mountain shale, also of Eocene age, outcrops. There are a number of road cuts in the area which expose small sections of the Lower Cockfield. The Cook Mountain shale section averages about 125 feet in thickness and rests directly on the Sparta sand, the core drill objective in the area.

Data from the records of Figure 7 may be seen plotted on Figure 8. Those curves are generally self-explanatory, but careful examination of the 90 foot curve will reveal that a few of the shallower points have been omitted. The missing points probably represented energy that was refracted and hence did not follow a straight line path from the shot to the seismometer.

A group of records from an area in the south central part of the Williston Basin are shown in Figure 9. Although the hole in which these records are taken was considerably deeper than those in North Louisiana and South Arkansas, energy presented no problem. Cable breaks did, however, prove troublesome, and it finally became necessary to move the seismometers out to a minimum distance of forty feet from the hole.

The area is generally a gently rolling plain with a few buttes and hills capped with soft to firm standstones. The valleys are eroded shale beds with some alluvium deposits near the streams. In a few places, small beds of lignite crop out in cut banks. Total relief of the area probably does not exceed 150 feet and there are no glacial deposits.

Data from the records of Figure 9 have been plotted in the graphs of Figure 10, along with the related Schlumberger and sample logs for the same hole. Although low velocity material appeared from time to time throughout the area, it was absent in this core hole. The 4,000 ft per second or intermediate layer extended down to about 150 ft and the velocity and thickness of this intermediate bed were found to vary greatly from point to point throughout the area.

Although no attempt has been made to set speed records, an average core drill with a minimum of experience can conduct velocity surveys at the rate of about seven minutes for every 100 ft of hole. That time could be further reduced if the operator chose to fire all the shots in the gun before developing the records. Up to now it has been customary to develop each record individually and to inspect it before proceeding with the next shot. That, no doubt, accounts to some degree for the high quality of the data obtained thus far.

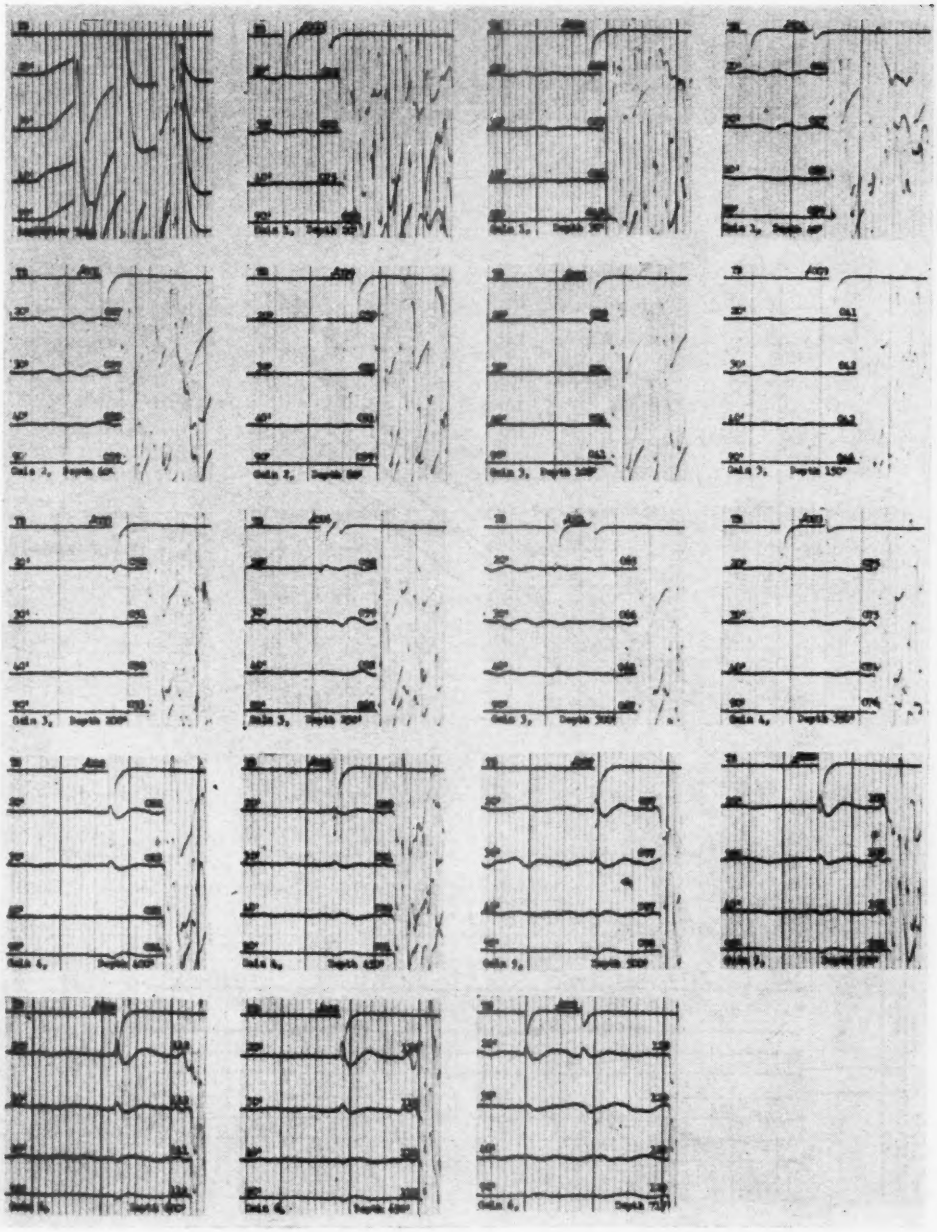

FIG. 7. Core Hole 15, Section 1, T16N-R2W, Vernon Area, Jackson Parish, Louisiana.

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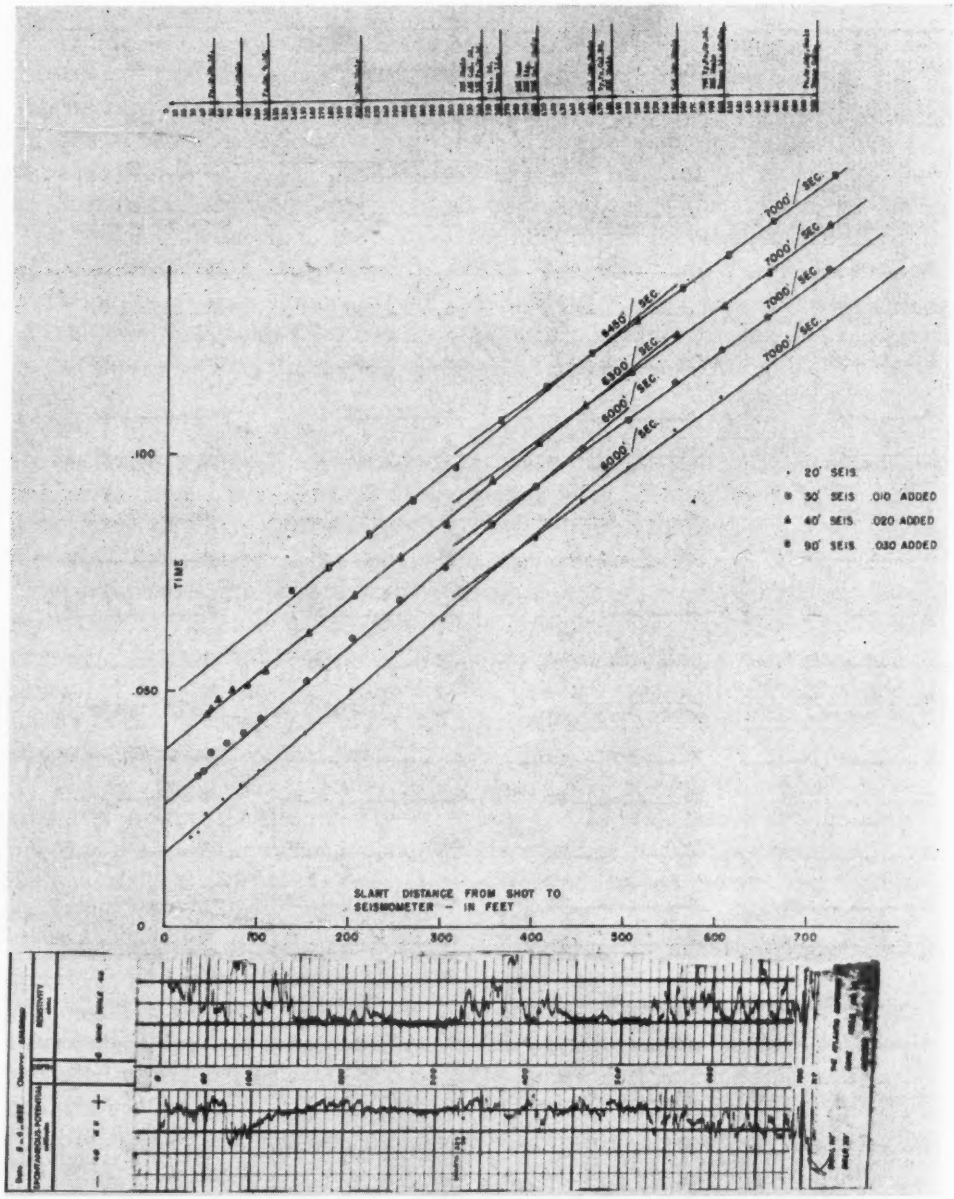

FIG. 8. Core Hole 15, Section 1, T16N-R2W, Jackson Parish, Louisiana.

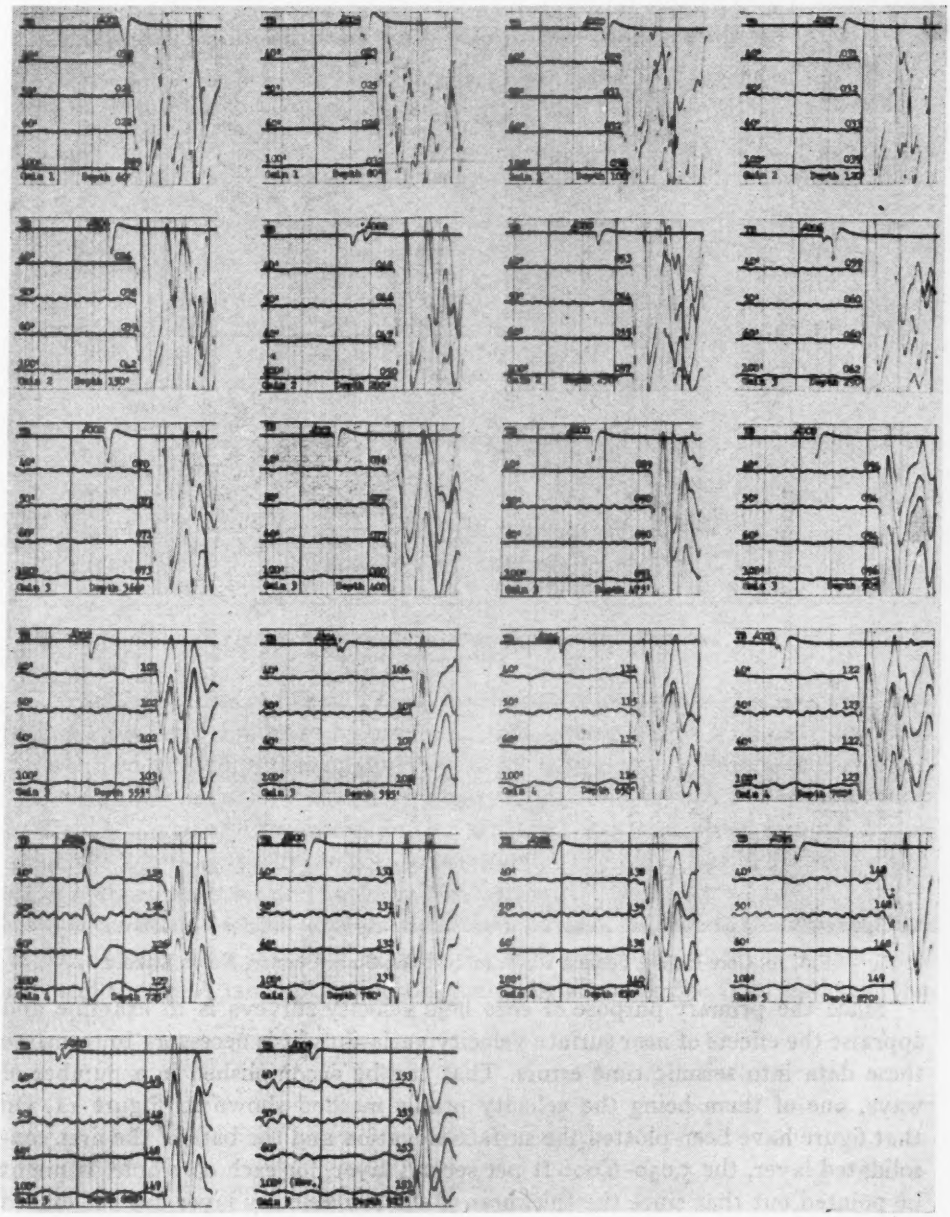

FIG. 9. Core Hole 3, Section 26, T140N-R79W, Stark County, North Dakota.

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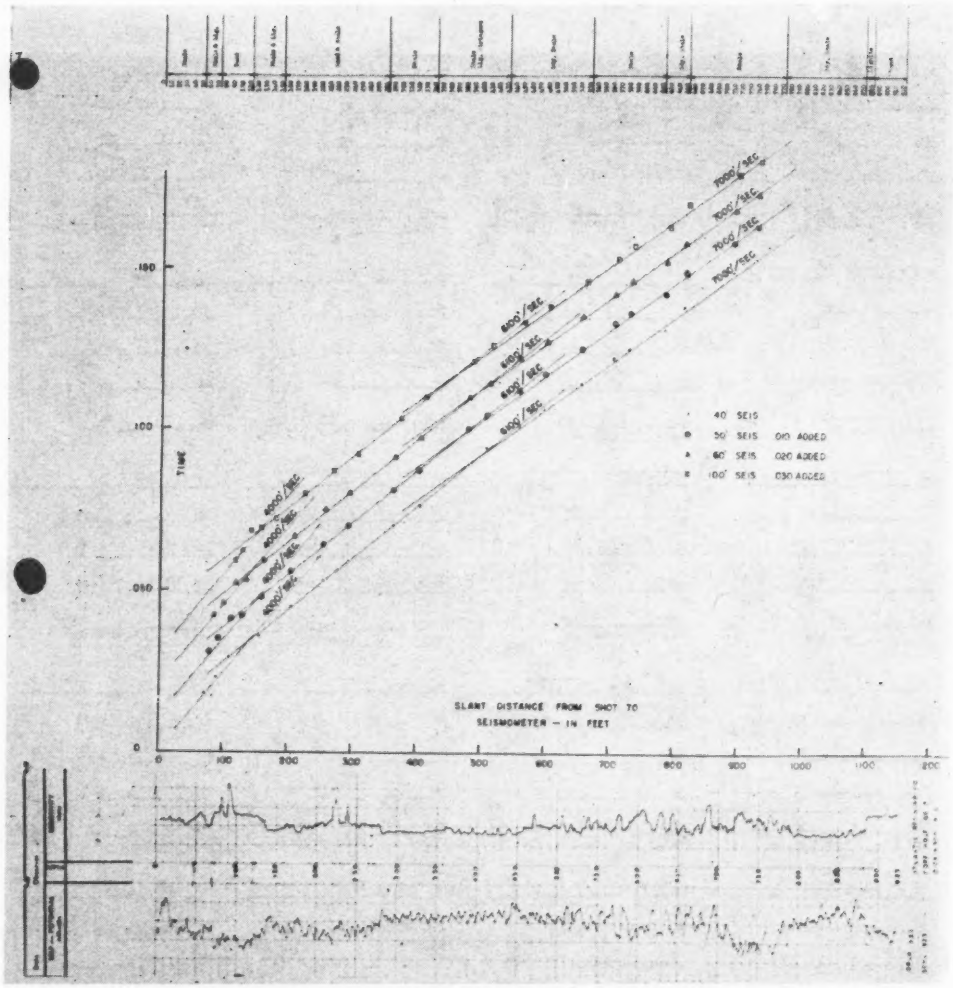


FIG. 10. Core Hole 3, Section 26, T140N-R97W, Stark County, North Dakota.

Since the primary purpose of core hole velocity surveys is to examine and appraise the effects of near surface velocity variations, it is necessary to translate these data into seismic time errors. That can be accomplished in a number of ways, one of them being the velocity profile method shown in Figure 11. On that figure have been plotted the surface elevation and the base of the first consolidated layer, the 5,030–6,000 ft per second layer, for each core hole. It might be pointed out that since the thickness of the low velocity layer did not exceed 20 ft, it was not measured in this group of surveys and is not considered to be of consequence. The base of the second consolidated layer velocity, 6,500–6,900 ft per second, was not penetrated by this group of holes and, therefore, cannot be shown.

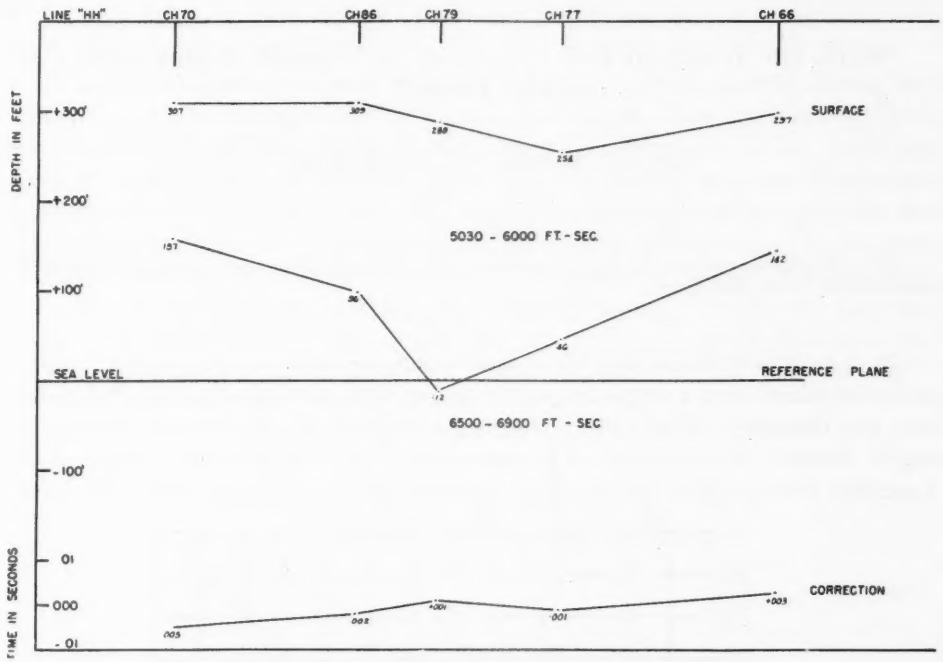


FIG. 11. Velocity profile, Columbia County, Arkansas.

Near the bottom of Figure 11 may be seen an error or correction curve. Those values have been computed by assuming that a seismic shot hole 50 ft deep had been drilled at each of the core hole locations. A two-way seismic time correction was computed to sea level assuming a correctional velocity of 6,000 ft per second, and then a similar time correction to sea level was computed using the true velocities as measured in the core hole surveys. The difference between the two values represents error and has been plotted as such.

The authors wish to express their appreciation to Mr. T. Y. Chang, Mr. H. D. Bolding, and Mr. F. P. Kokesh for their generous assistance in this project, and to The Atlantic Refining Company for allowing the information to be published.

NOTE ON WAVE-GUIDE PROPAGATION OVER A SHALLOW SALT DOME*

LYNN G. HOWELL† AND C. H. KEAN†

ABSTRACT

This note shows evidence of a duct or wave-guide type of wave propagation over a shallow salt dome located in the Gulf Coast.

In 1940 Howell, Kean, and Thompson[1] published some results on wave propagation obtained with a single-frequency source. One particular profile was made over the Hawkinsville salt dome, where the cap rock is only 100 to 200 feet in depth. Figure 1 shows a copy of the travel time curve obtained to a distance of 1,200 feet from a source generating a 400 cycle-per-second pulse. Also, the point

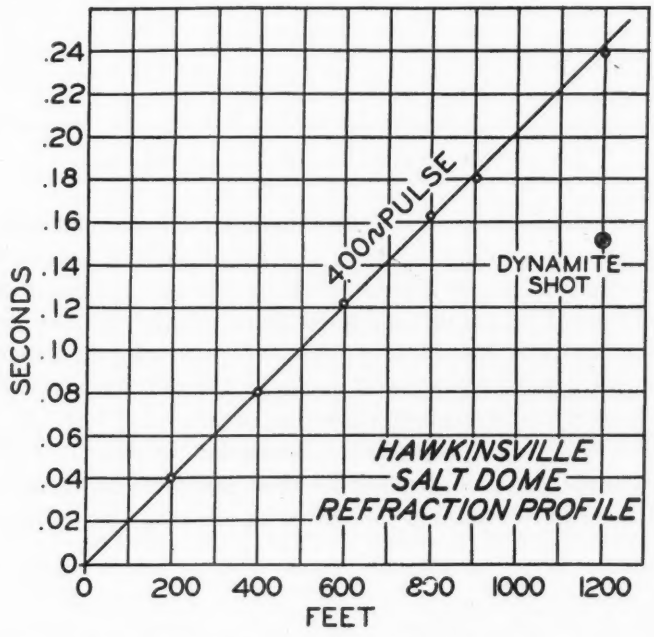


FIG. 1. Refraction profile made over Hawkinsville Salt Dome, Texas.

obtained with a dynamite pulse at 1,200 feet is shown. It was pointed out that the 400 cycle pulse arrived with a velocity of about 5,000 feet per second, which is

* Manuscript received by Editor November 8, 1952.

† Humble Oil and Refining Company, Houston, Texas.

[1] L. G. Howell, C. H. Kean, R. R. Thompson, *Geophysics*, V, 1, (1940) pp. 1–14.

very close to the velocity of sound in water, while the dynamite pulse arrived with a much higher velocity.

These results are of interest in view of the more recent work of Ewing and Pekeris[2] on wave propagation in a shallow water layer. They have shown, both experimentally and theoretically, that dispersion occurs for waves travelling through shallow water overlying a higher-velocity bottom medium. The progagation is of the wave-guide type. The wave first arriving from an explosion has a low frequency and travels with a phase and a group velocity equal to the compressional velocity in the lower medium. The frequency of the following wave progressively becomes higher until later a high frequency train arrives superimposed on this first train. The phase and the group velocity of the beginning of the

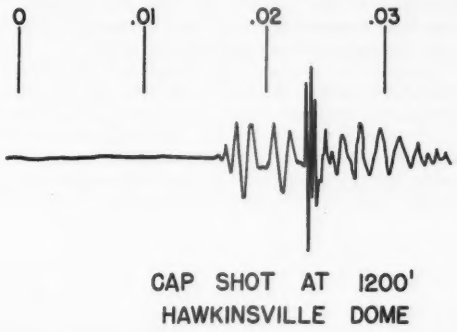


FIG. 2. Recording made from explosion.

high frequency train are equal to the velocity of sound in water. The frequency of the second train decreases until it merges with the first train to form the Airy phase, in which both trains have the same frequcny.

Figure 2 shows a tracing of a seismogram made at the 1,200 ft travel distance over the Hawkinsville salt dome; the seismogram was not published in the earlier paper. This is a pressure recording from a primer cap explosion. There is a slight uncertainty about the time of explosion, but this is not serious. The record shows some of the characteristics of wave-guide propagation. The first arriving wave train has a low frequency and exhibits a group velocity higher than the velocity of the shallow water table, presumably the velocity of the cap rock or a layer slightly above the cap rock. The large amplitude beginning of the high-frequency train arriving at about 0.23 second exhibits a group velocity of about the velocity of sound in water, presumably that of the shallow water table. The dispersion exhibited by this record is not as uniform as that obtained by Ewing in shallow water work, probably due to a somewhat more complicated layering. A further indication of the wave-guide type of propagation is the surprisingly small attenuation of the 400 cycle pulse mentioned in the original article.

[2] Ewing, Worzel, Pekeris, "Propagation of Sound in the Ocean," The Geological Society of America, Memoir 27 (October 15, 1948).

OIL AND GAS EXPLORATION IN ALABAMA, GEORGIA, AND FLORIDA*

ROBERT B. BAUM†

ABSTRACT

The discovery of the Pollard oil field in southern Alabama early in 1952 sparked a campaign of leasing and exploration which spread quickly into Georgia and Florida. Three fields in southwestern Alabama and one in southern Florida account for all the oil production in the three states.

Some aspects of the general geology and geophysics of the area, illustrated with maps, cross sections, and correlation charts, suggest the presence of geologic conditions favorable for the possible trapping and accumulation of oil and gas.

Early seismograph exploration in much of the area was not effective, but in recent months the tempo of seismic activity has been accelerating, and improvements in instrumental and interpretive techniques are being achieved through current experimental work.

The use of the various geophysical methods contributed to the discovery of the four oil fields located in the area. The structural traps indicated by the contour maps of the four fields are of the type sought by the reflection seismic method. Examples of representative reflection records indicate the presence of usable and correlatable seismic events. A seismic cross section prepared from data of this type shows the fault zone associated with the Pollard field.

The existence of favorable geologic conditions in the southeastern states and the recent oil field successes at Pollard and South Carlton indicate the continuing of active development and exploration throughout the area.

INTRODUCTION

In September, 1951, significant shows of light oil were tested in a southern Alabama wildcat well drilled by Stanolind Oil and Gas Company. The test was located a few miles north of the Florida state line, on the F. A. Steward property in Escambia County, SE SE Section 11, Township 1 North, Range 8 East. The oil was found in lower Tuscaloosa sands of Upper Cretaceous age, 5,938 to 5,959 feet in depth. Although the well was abandoned as non-commercial, this showing of oil, at a location considerably east of present production in the southern Alabama area, led to the discovery of the adjacent Pollard field in January, 1952. It was this discovery that sparked a campaign of exploration and leasing which spread throughout southern Alabama, southern Georgia, and the Florida panhandle. It indirectly may have encouraged exploratory efforts in the southern part of Florida.

The purpose of this paper is to describe some of the general geology and exploration geophysics of Alabama, Georgia, and Florida in relation to potential oil and gas production.

GENERAL GEOLOGY

An index map of the southeastern part of the United States showing the oil fields in Alabama and Florida and the northern gas area of Mississippi and Ala-

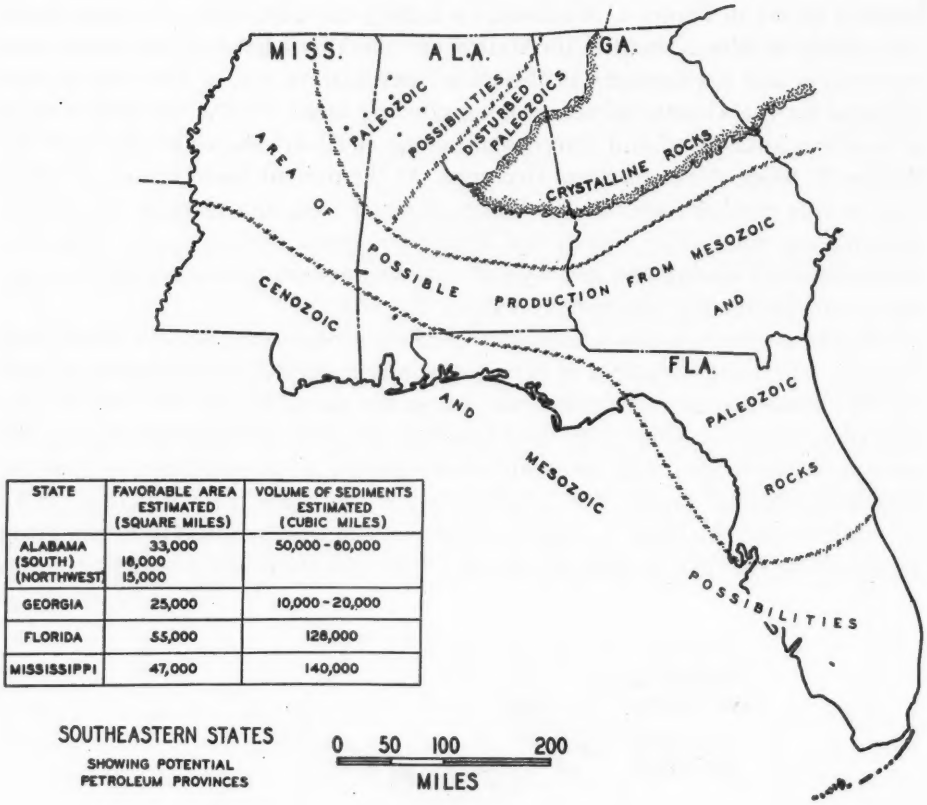
* Presented at the Ft. Worth Regional Meeting November 1952. Manuscript received by the Editor January 14, 1953.

† Seismograph Service Corporation.

bama is shown in Figure 1. Mississippi is largely excluded from discussion since the petroleum development in the state is considerably advanced as compared to exploration and development in the other southeastern states. The map is conspicuous by the absence of numerous producing areas. In the northern area a belt of four abandoned and three potential gas fields are shown as described by Walter B. Jones, Alabama State Geologist. At the present time the only production in this northern province is being obtained from the recently discovered Muldon gas field which lies in the Mississippi portion of the area. This discovery spurred leasing and geophysical activity, and many seismic parties currently are conducting surveys throughout the area.

Southwestern Alabama boasts three oil fields: Gilbertown, South Carlton, and Pollard. The Langsdale field of Mississippi was extended into Alabama in 1951 by the completion of a producing well across the state line, but this field is considered primarily a Mississippi development. The only other production in the area is obtained from the Sunniland field located in the southern part of the Florida peninsula. Except for Sunniland, the vast area lying east and south of southwestern Alabama is barren of commercial production. Oil is not being produced in Georgia in spite of the fact that the state has a standing bonus

FIG. 1. Southeastern states, showing Alabama-Florida oil fields and northern gas area.



STATE	FAVORABLE AREA ESTIMATED (SQUARE MILES)	VOLUME OF SEDIMENTS ESTIMATED (CUBIC MILES)
ALABAMA (SOUTH) (NORTHWEST)	33,000 18,000 15,000	50,000 - 60,000
GEORGIA	25,000	10,000 - 20,000
FLORIDA	55,000	128,000
MISSISSIPPI	47,000	140,000

FIG. 2. Southeastern states, showing potential petroleum provinces.

offer of $100,000.00 to the operator bringing in the first 200-barrel well.

The potential petroleum provinces of the region as outlined in 1941 and 1951 by the A.A.P.G. are shown in Figure 2. The map indicates the northwestern part of Alabama as favorable for possibilities from Paleozoic beds, while the entire area of Mississippi and Florida and most of the southern portions of Alabama and Georgia appear favorably situated with respect to potential production from younger beds. The table at the lower left shows the area favorable for possible production and indicates the estimated volume of sedimentary deposits underlying these areas. Since quantities such as these are difficult to evaluate, a more effective means of comparing the size of the area under discussion is indicated in Figure 3, where the state of Texas is superimposed over the index map of the southeastern states: Since a large portion of Texas is observed to lie in the Gulf of Mexico water area of the index map, a land-to-land comparison is achieved in Figure 4 by placing those land areas of the southeastern states, which extend beyond the Texas borders, into the Gulf of Mexico. The two il-

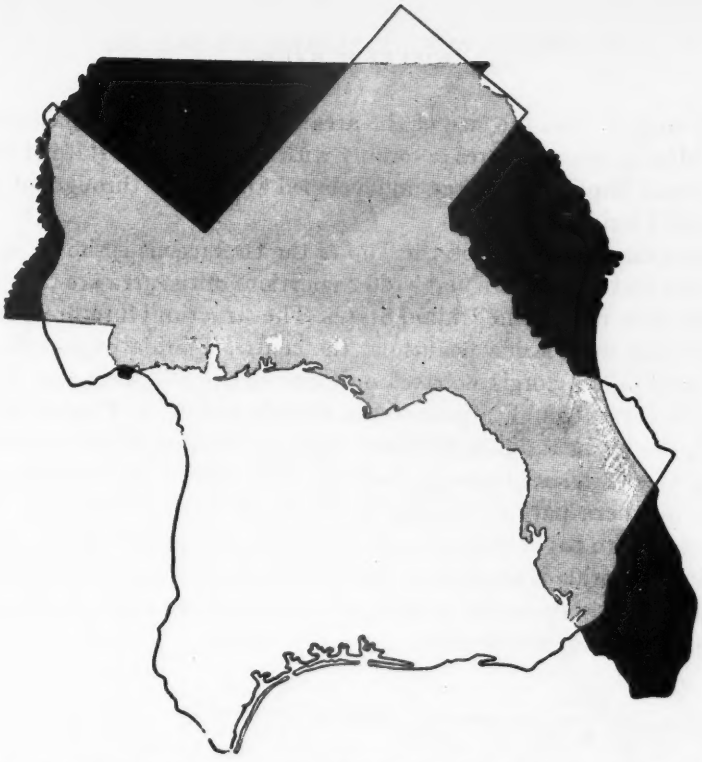


FIG. 3. Index map of southeastern states, with state of Texas superimposed.

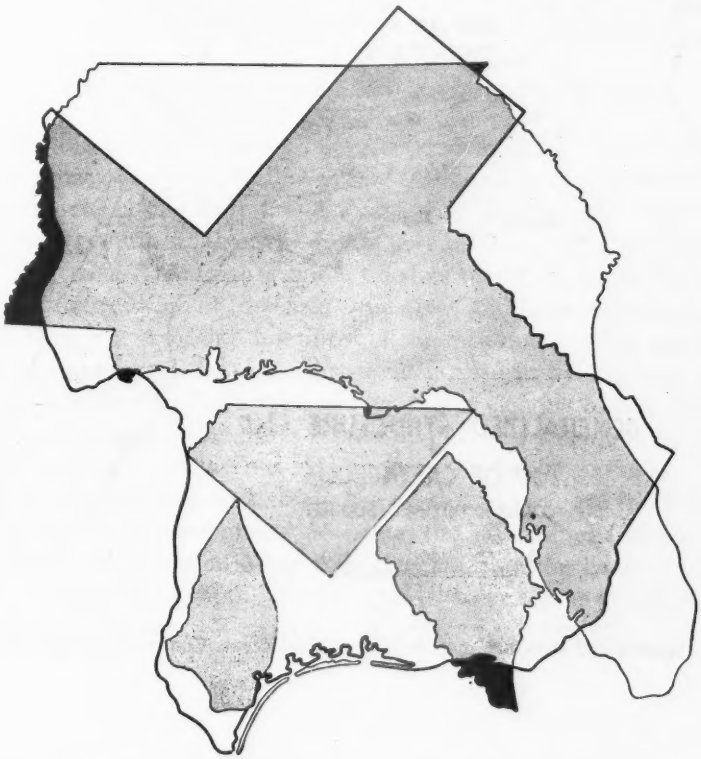


FIG. 4. Texas and southeastern states, land-to-land comparison.

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lustrations suggest that the size of the area comprising the southeastern states, including Mississippi, compares favorably with the size of the state of Texas, and the comparison implies that large undeveloped areas exist throughout Alabama, Georgia, and Florida.

The generalized structure on the Top of the Cretaceous is shown in Figure 5. The contours for the northern and western portions of the area are taken from the familiar Tectonic map of the United States. The structural interpretation for the area comprising the Florida peninsula, the central Florida panhandle, and the southern portion of Georgia is based on more recent well data and on material appearing in current publications of the Florida and U. S. Geological Surveys. In general, the regional dip in southern Alabama is south-southwestward, interrupted by the Hatchetigbee anticline and the north-south trending Jackson fault. The northern part of Georgia is blanketed by Paleozoic and crystalline rocks, the southern part showing south-to-southeast regional dip. In general, the regional dip in Florida is southward, modified by the feature in the northern part of the peninsula known as the Ocala Uplift, the southern flank of which develops into the south Florida embayment.

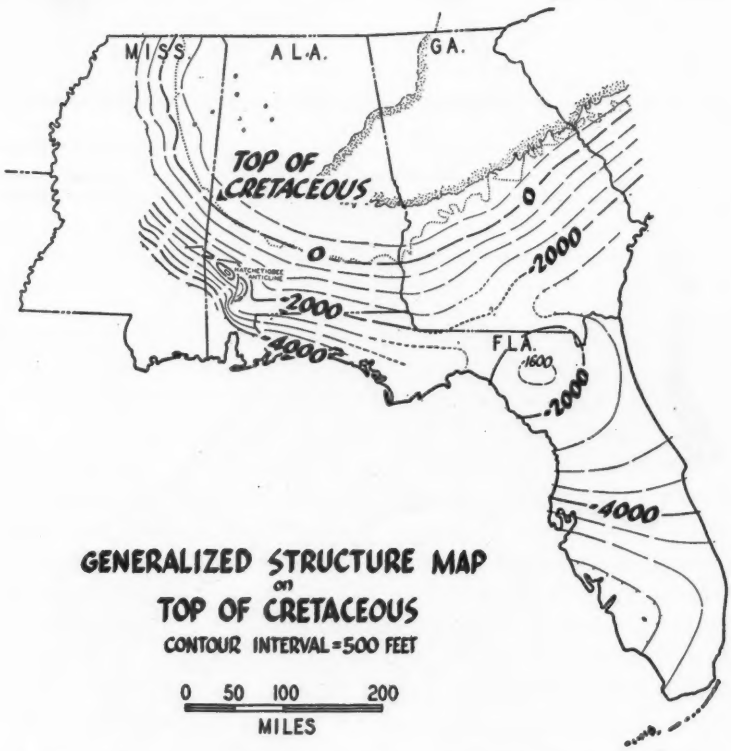


FIG. 5. Generalized structure map on Top of Cretaceous. Contour interval=500 feet.

FIG. 6. Approximate outline of basin areas and associated features.

The Applins' study of lower Upper Cretaceous beds (Oil and Gas Investigations Preliminary Chart 26, United States Geological Survey), depicts a development of regional nosing near the Alabama-Georgia-Florida common boundary which is more prominent than the gentle nose indicated by the structure on the Top of Cretaceous. This feature is identified as the Marianna or Decatur uplift. The approximate outline of the basin-type areas and associated areas of uplift is shown in Figure 6. A basin, described as the Suwannee Strait and believed to result from an erosional feature subsequently filled in by Tertiary beds, is depicted as connecting the Southwest and Southeast Georgia basins. Evidence supporting the opinion that the basin is erosional in nature is found by the absence of beds of the Upper Cretaceous Navarro and Taylor formations.

Other general features outlined to the north and west are the Black Warrior basin in northern Mississippi and Alabama, the Mississippi Interior Salt basin, and the up-dip edge of a Miocene basin identified as the Eastern Gulf embayment. The Central Mississippi "Ridge" appears to be a zone of regional terracing which separates the Black Warrior and Mississippi Salt basins.

Cross sections are presented in Figures 7 and 8 which appear to indicate that regional stratigraphic and structural conditions in Alabama, Georgia, and Florida warrant further exploration. Figure 7 represents a profile based on 18 wells along the line AB (Fig. 1) and extends from a deep test in western Alabama southeastward to northeastern Florida. Jurassic and Ordovician beds are reached only in wells at the northwestern part of the profile, with basement rock encountered underlying the Cretaceous east of the central Florida panhandle. A large regional unconformity is known to be present at the base of the Upper Cretaceous in southern Alabama and is observed on the cross section. Actually, Upper Cretaceous beds rest on igneous or Paleozoic rocks in central Alabama.

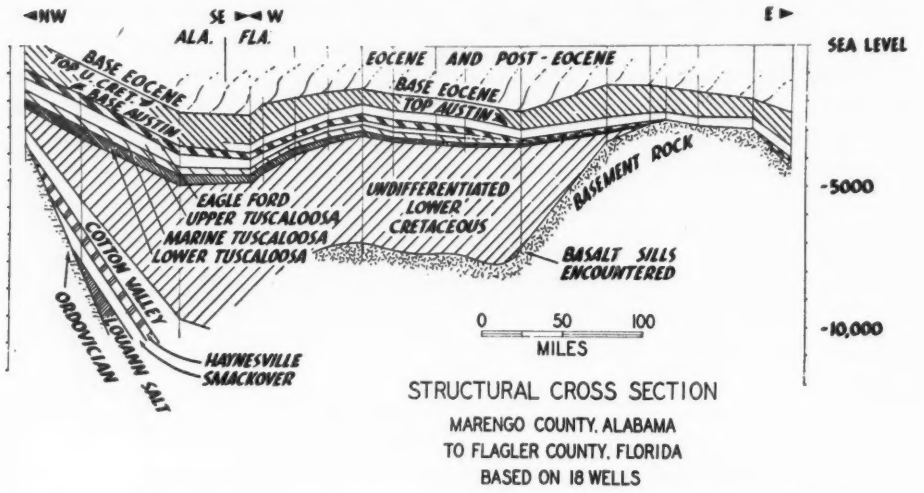
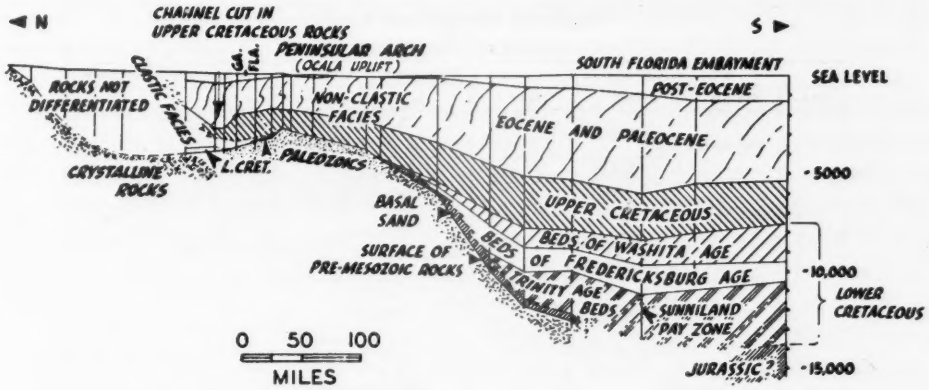


FIG. 7. Structural cross section, Marengo County, Alabama to Flagler County, Florida—Based on 18 wells.

Farther downdip the Lower Cretaceous formations wedge in and probably rest on igneous and Paleozoic rocks also. A rather thick Cretaceous section with apparently favorable development of the Tuscaloosa zone is observed in the southern Alabama-northwestern Florida area. A thick Cretaceous section is also shown to develop west of the Ocala Uplift with beds of pre-Austin age appearing to wedge out on both flanks of the feature.

The north-south cross section (Fig. 8) is taken from the 1952 Florida Geological Survey Guidebook and depicts structure along the line CD (Fig. 1) from the outcrop of crystalline rocks in central Georgia southward to the Florida keys. The erosional feature on the north flank of the Ocala Uplift described earlier is indicated in cross-section as a channel cut in Upper Cretaceous rocks. Clastic facies appear to predominate north of the uplift and non-clastics to the south, with marine sediments ranging from 50 percent in the north to almost 100 percent in the south. A thick Cretaceous section is shown to develop down-dip into



STRUCTURAL CROSS SECTION
FROM OUTCROP OF CRYSTALLINE ROCKS IN CENTRAL GEORGIA TO BIG PINE KEY, MONROE COUNTY, FLORIDA
BASED ON 22 WELLS
(AFTER FLORIDA GEOLOGICAL SURVEY)

FIG. 8. Structural cross section. From outcrop of crystalline rocks in central Georgia to Big Pine Key, Monroe County, Florida—Based on 22 wells. (After Florida Geological Survey.)

the embayment. The Upper Cretaceous beds overlap all the older formations from south to north, and locally rest on metamorphic rocks in the north.

A generalized correlation chart for Mississippi, Alabama, southern Georgia, and Florida (Fig. 9) was developed from a number of reliable correlation charts prepared for use in the general area. The attempt is not made to distinguish between the nomenclature of surface and subsurface beds, and only the terminology more commonly employed by the various sources are used in the chart. An indefinite boundary between the Alabama and Florida terminology is shown purposely, since nomenclature is used which is common to both areas of southern Alabama and northwestern Florida. Currently, principal exploration interest in southern Alabama and northwestern Florida appears centered in the lower part of the Upper Cretaceous beds, a zone which is a rich producer of oil in East Texas and North Louisiana. This formation is identified as the familiar Woodbine in northeastern Texas and is correlated as the time-rock equivalent of the middle and lower Tuscaloosa of Mississippi and Alabama, and of the middle and lower Atkinson formation of southern Georgia and northern Florida.

GEOPHYSICAL ACTIVITY

At the present time geophysical exploration of the area is accelerating appreciably, especially with the seismograph. Unlike most other favorable sedimentary provinces, thorough testing of the seismic method in Alabama, Georgia,

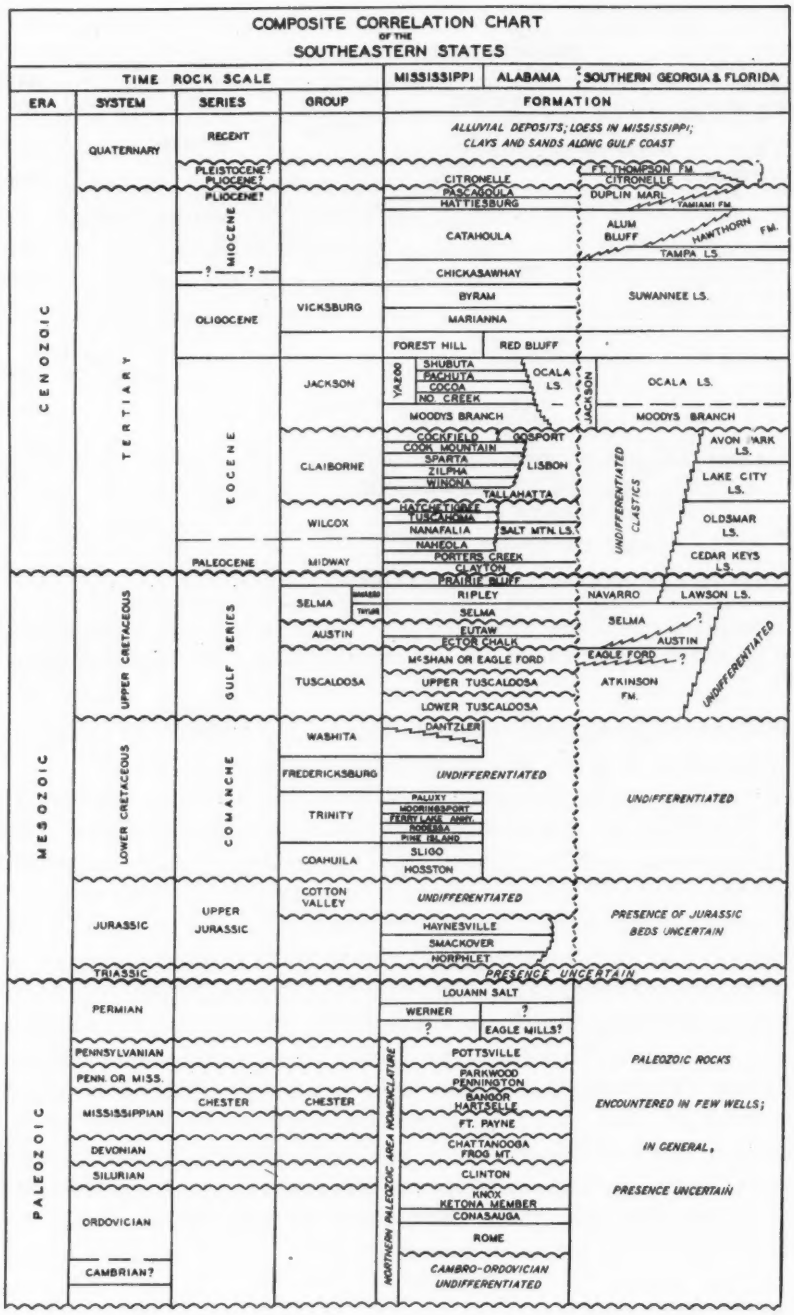


FIG. 9. Composite correlation chart of the Southeastern States.

and Florida is just beginning. The reason the method was not used extensively until recently probably lies in its past failure to provide satisfactory and consistent reflection records.

From 1943 through 1951 the exploratory activity per unit of area in the three southeastern states was considerably less than activity in other petroleum areas such as North Louisiana (Fig. 10). It is apparent from the graph that prior to 1948 the gravity method was used more widely than the seismograph in the Alabama-Georgia-Florida area, but the trend appears to have been reversed in 1949. According to present activity reports, the year 1952 will be a record year

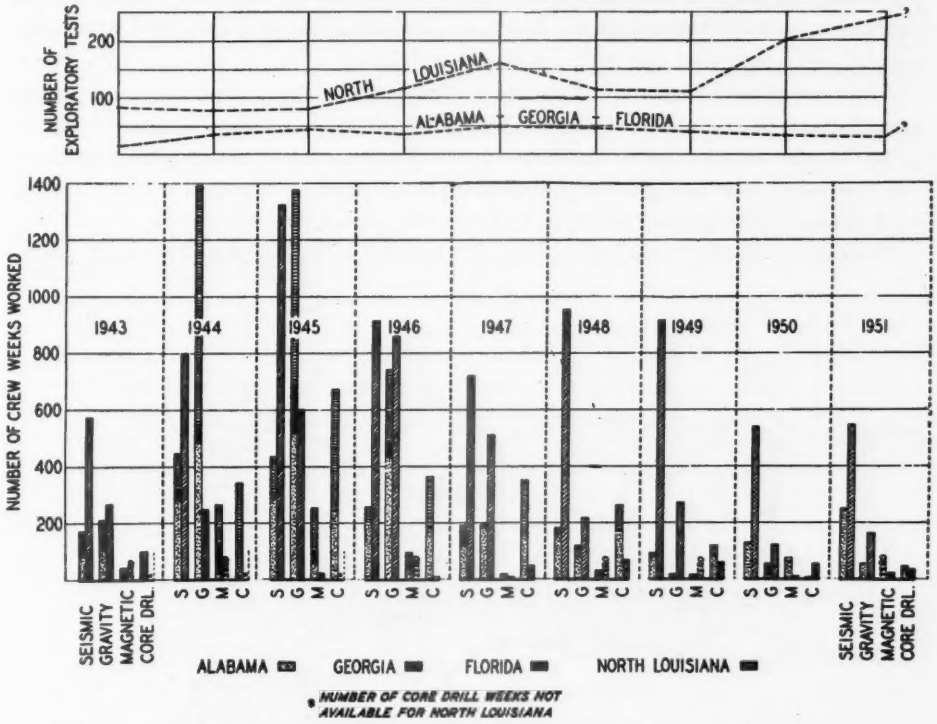


FIG. 10. Graph showing geophysical and exploratory activity from 1943 through 1951.

for the employment of seismograph crews. It appears evident that a sharp rise will be recorded also in the number of wildcat tests drilled. The core drill has been used extensively and is now being employed in southwestern Alabama and northwestern Florida where the deeper structure is believed to be reflected by shallow horizons such as the Eocene Salt Mountain and Ocala limestones.

RELATION OF GEOPHYSICAL RESULTS TO GEOLOGY

A portion of the regional Bouguer gravity map published by Nettleton in *Geophysics*, July, 1949, is reproduced in Figure 11. The minimum trend in

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east-central Alabama and the adjacent maximum trend farther south near the Georgia-Alabama state line may represent a continuation of the plunging Appalachian structural trends, but these indications are not definite. A maximum trend is observed across the northern Florida peninsula, which may correlate with the Ocala structural uplift. The deeper part of the basin in southern Florida may be reflected by the gravity minimum indicated in this area.

The regional magnetic map of southwestern Alabama shown in Figure 12 is prepared from the detailed study of Nicar and Eby published by the Alabama Geological Survey in 1936. This map, modified to show 50 and 100 gamma contour intervals only, is presented since it encompasses an area in or adjacent to which are located the three oil fields of Alabama, each discovered since the original preparation of the map by Nicar and Eby.

Four prominent regional maximum anomalies and three prominent minimum anomalies are depicted. The general magnetic picture does not appear to be affected by the Hatchetigbee anticline or the Jackson fault. Nicar and Eby indicate, however, that the general magnetic contour pattern suggests the southwestward extension of the buried Appalachian Paleozoics.

Favorable results were not obtained with the seismic method in past years.

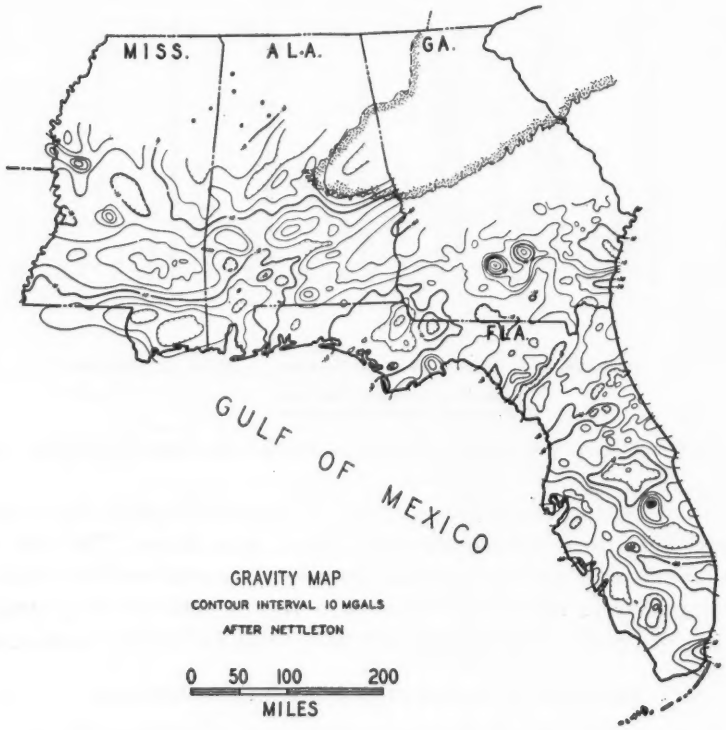


FIG. 11. Gravity map. Contour interval 10 mgals. (After Nettleton.)

Since sufficiently thick sections of favorable reservoir rocks are indicated to underlie most of the area (Figs. 7 and 8), it is inferred that the failure to find more than four oil fields in Alabama, Georgia, and Florida lies in the absence of a usable tool for locating structural traps. The type of traps involved at each of the four oil fields are shown by the structural contour maps of the field areas.

The Sunniland field in Collier County, Florida (Fig. 13), was discovered in November, 1943, on completion of the Humble Oil and Refining Company No. 1 Gulf Coast Realties Corporation well. Lower Cretaceous production was obtained from porous limestone in the Sunniland zone at a depth in excess of 11,600 feet. The structure controlling the oil accumulation appears to be anticlinal with the axis extending in a northwest-southeast direction. The field area is reported to lie in a saddle between two gravity maxima, with seismic, gravity, and core drill results contributing to its discovery.

The Humble discovery well at Sunniland was the first to produce oil in the

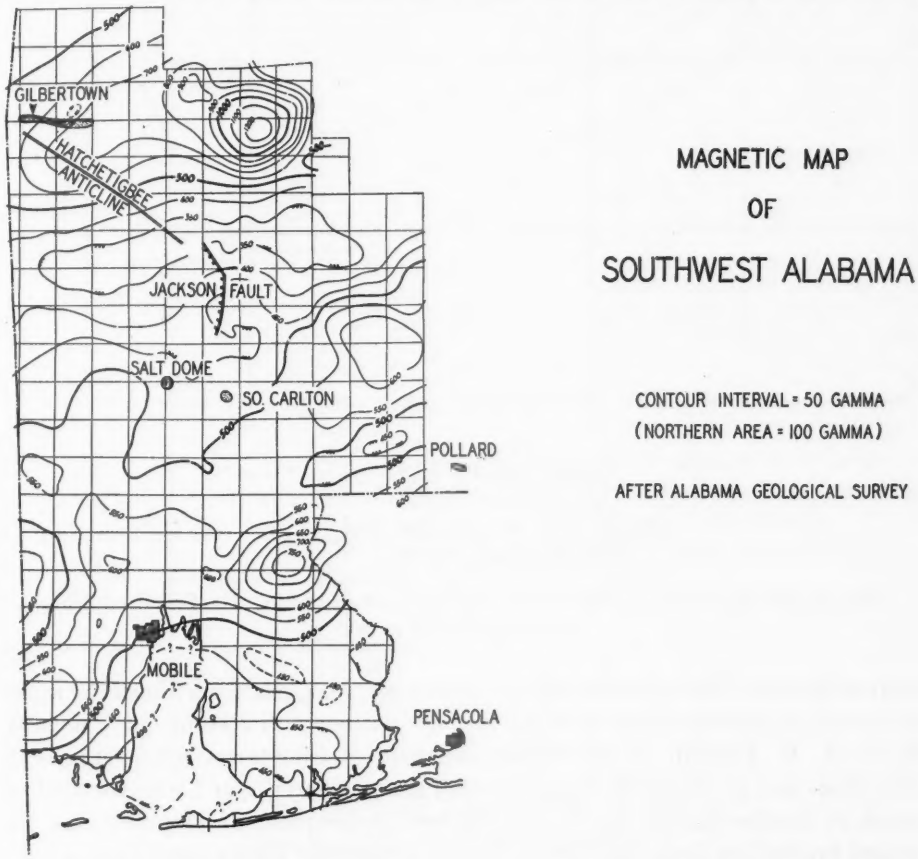
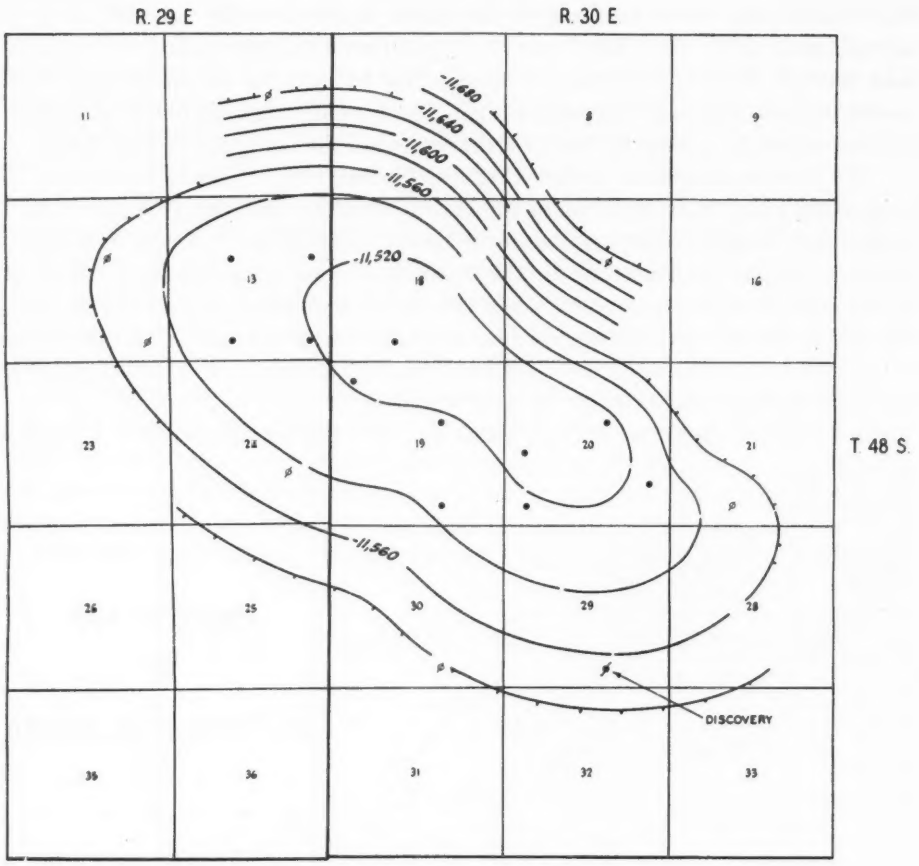


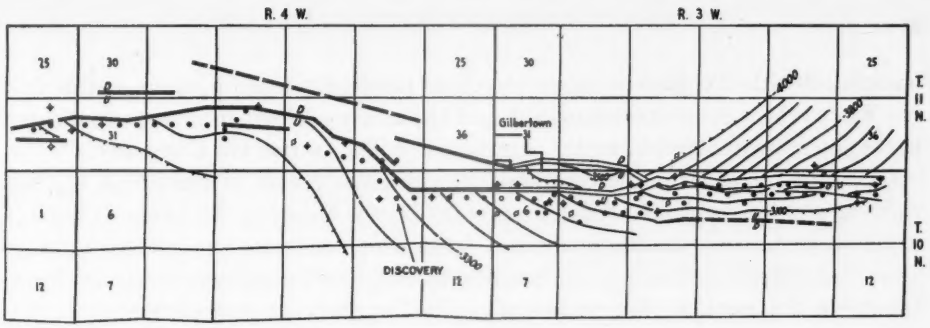
FIG. 12. Magnetic map of southwest Alabama. Contour interval=50 Gamma (Northern Area=100 Gamma). (After Alabama Geological Survey.)



SUNNILAND FIELD
COLLIER COUNTY, FLORIDA
CONTOUR DATUM: TOP SUNNILAND ZONE
CONTOUR INTERVAL = 20 FEET

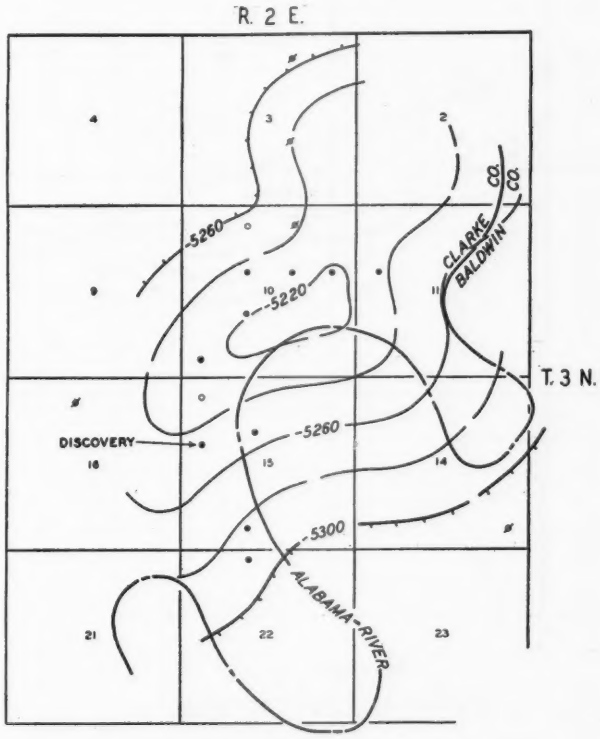
FIG. 13. Sunniland Field. Collier County, Florida. Contour Datum: Top Sunniland Zone. Contour interval = 20 feet.

state of Florida. Three months later, in February, 1944, Alabama joined the ranks of the oil producing states with its first oil discovery, the Hunt Oil Company No. 1 A. R. Jackson, in the Gilbertown field of Choctaw County (Fig. 14). The Hunt test produced oil from fractured zones in the Upper Cretaceous Selma chalk at depths slightly less than 2,600 feet. Subsequent development has obtained production from both the chalk and underlying Eutaw sands, also Upper Cretaceous in age. The production is controlled principally by down-to-the-north faulting. The fault zone appears to be part of a fairly complex system of faulting



GILBERTOWN FIELD
CHOCTAW COUNTY, ALABAMA
CONTOUR DATUM: TOP EUTAW
CONTOUR INTERVAL = 40 FEET

FIG. 14. Gilbertown Field, Choctaw County, Alabama. Contour datum: Top Eutaw. Contour interval=40 feet.

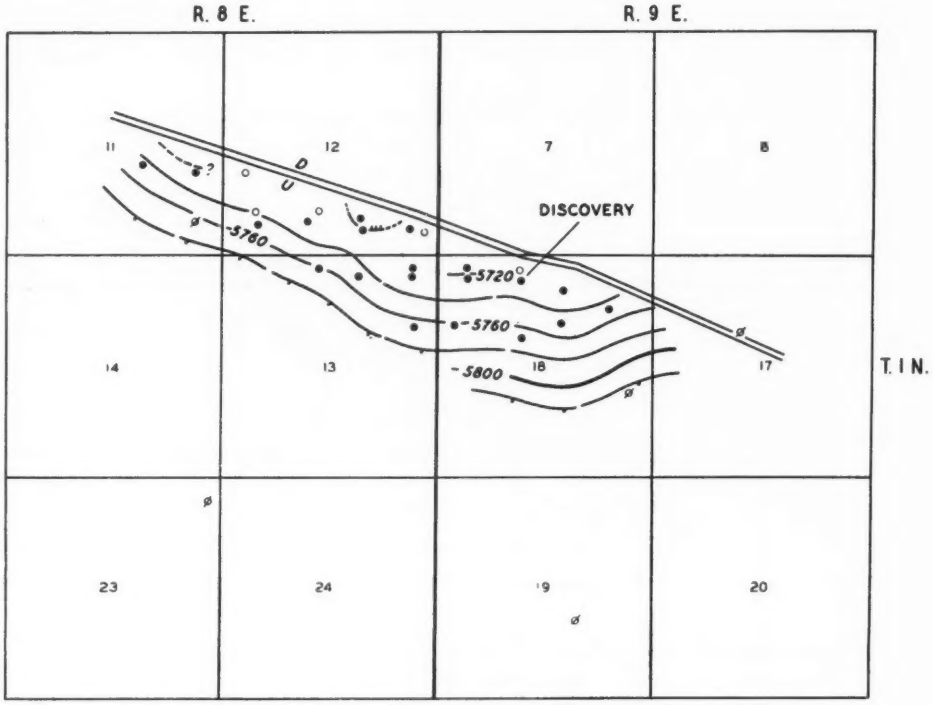


SOUTH CARLTON FIELD
CLARKE AND BALDWIN COUNTIES, ALABAMA
CONTOUR DATUM: TOP LOWER TUSCALOOSA SAND
CONTOUR INTERVAL = 20 FEET
AS OF DECEMBER 1, 1952

FIG. 15. South Carlton Field, Clarke and Baldwin Counties, Alabama. Contour datum=Top Lower Tuscaloosa Sand. Contour interval=20 feet. As of December 1, 1952.

associated with the Hatchetigbee anticline. Credit for the discovery of this field is given to the reflection seismograph and to surface geology. The structural interpretation shown is presented by permission of The Carter Oil Company.

In May, 1950, Humble completed the discovery well of the South Carlton field as its No. 1 J. H. Wall Estate in Clarke County, Alabama (Fig. 15). Upper Cretaceous production in the field, which extends across the Alabama River into Baldwin County, is obtained from lower Tuscaloosa sands at depths in excess of 5,400 feet. The structure controlling the oil accumulation appears to be anticlinal with an axis shown to trend northeast-southwest. The structure is believed associated with a deep seated salt dome and is reported to be reflected as a gravity minimum. Core drill and seismic methods also were employed in exploring the area.



POLLARD FIELD
ESCAMBIA COUNTY, ALABAMA

CONTOUR DATUM: TOP LOWER TUSCALOOSA SAND
CONTOUR INTERVAL = 20 FEET

AS OF DECEMBER 1 1952

FIG. 16. Pollard Field. Escambia County, Alabama. Contour datum = Top Lower Tuscaloosa Sand. Contour interval = 20 feet. As of December 1, 1952.

In January of this year feverish exploration and leasing activity was sparked by the discovery of the Pollard field (Fig. 16) in Escambia County, Alabama, some forty miles southeast of South Carlton. Lower Tuscaloosa sands approximately 5,950 feet in depth were found productive at the Humble No. 1 Moye discovery well, the potential for which was estimated at 1,000 barrels per day. The production appears to be controlled by closure against the upthrown side of a northwest-southeast trending fault, downthrown to the north. Subsequent testing in wells drilled to the deeper Tuscaloosa Massive sand were also successful. Exploration with the core drill appears to have contributed to the discovery of this field.

The structural traps indicated at the four oil fields illustrated are of the type commonly sought by the reflection seismic method. Satisfactory results obtained

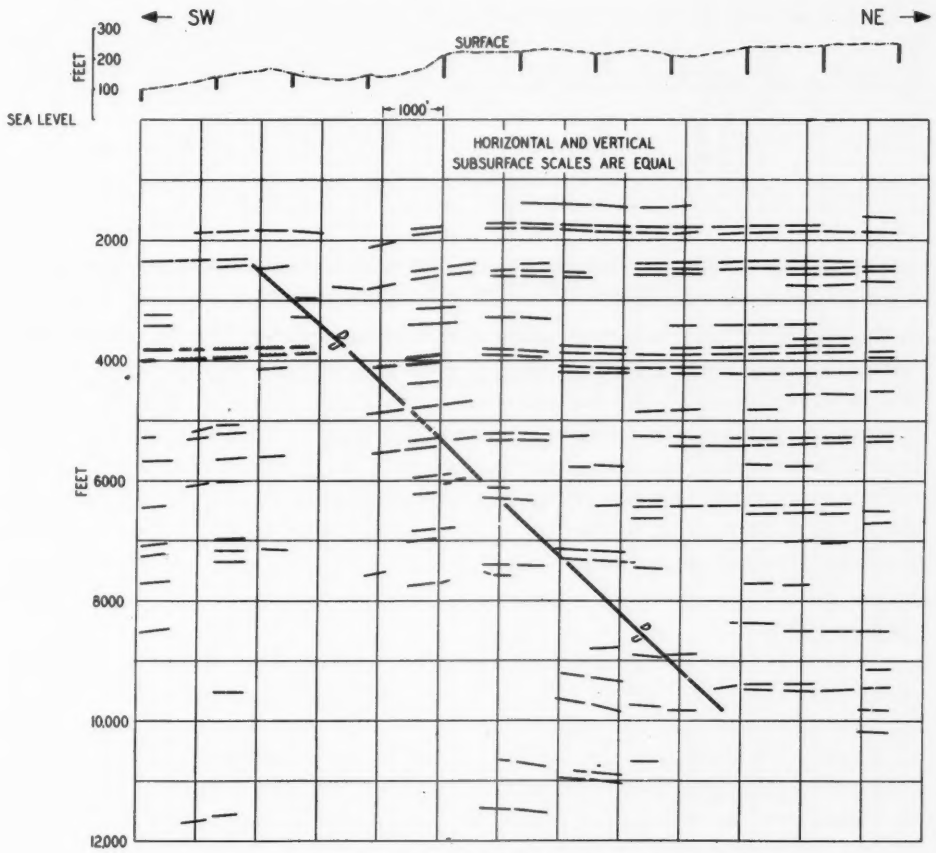


FIG. 17. Seismic cross section across Pollard Field, Escambia County, Alabama.

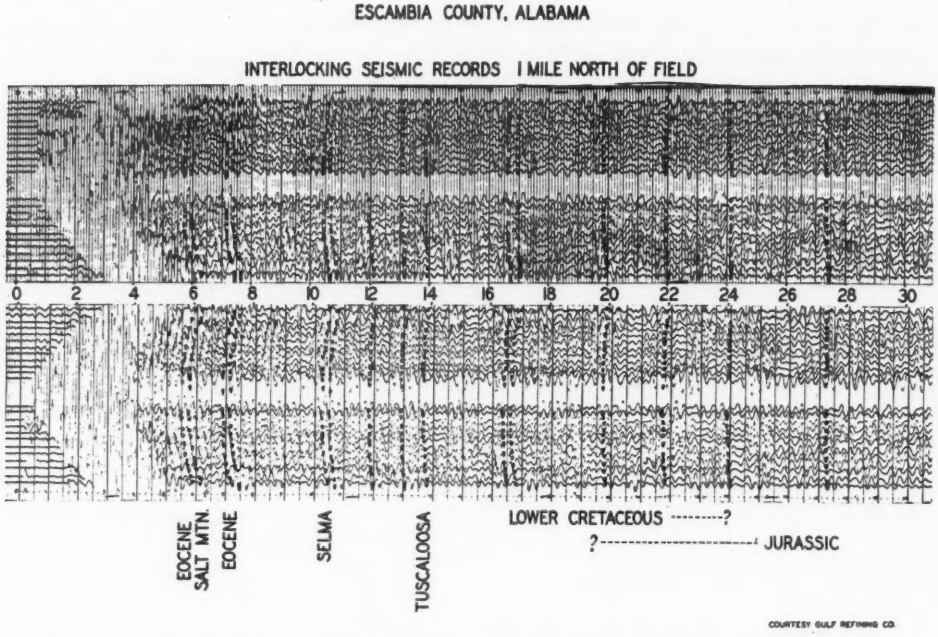

POLLARD FIELD AREA
ESCAMBIA COUNTY, ALABAMA
INTERLOCKING SEISMIC RECORDS 1 MILE NORTH OF FIELD
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
EOCENE SALT MTN.
EOCENE
SELMA
TUSCALOOSA
LOWER CRETACEOUS --------?
?---------- JURASSIC
COURTESY GULF REFINING CO.

FIG. 18. Pollard Field area. Escambia County, Alabama. Interlocking seismic records 1 mile north of field. (Courtesy Gulf Refining Co.)

in the area from its use in past years were seldom reported. At the present time refraction techniques are being employed throughout the land areas of Florida and in its waters along the western coast by various companies. Results are considered favorable. Recent efforts by some oil companies and seismic contractors have also indicated encouraging reflection results. It was recognized that considerable experimenting and research were necessary before satisfactory reflection data could be obtained. While much is still to be desired in this respect, substantial improvement in instrumentation, field procedures, and interpretive techniques has been achieved in certain areas from operations of production and research crews.

A seismic cross section, presented by permission of Gulf Refining Company, shows the dips of subsurface reflections obtained from a traverse extending approximately 2½ miles in a northeast-southwest direction across the Pollard field (Fig. 17). The bearing of the traverse is normal to the strike of the major fault indicated by the well data. The fault is shown on the cross section as determined by data from the well across which the seismic profile was surveyed. The dips shown were computed by continuous profile methods. In addition, individual depth points were plotted for each of the geophone stations lying between the shot points occupied. Sufficient reflection data are evident on the cross section to indicate the existence of faulting. Selma chalk reflections are correlated on

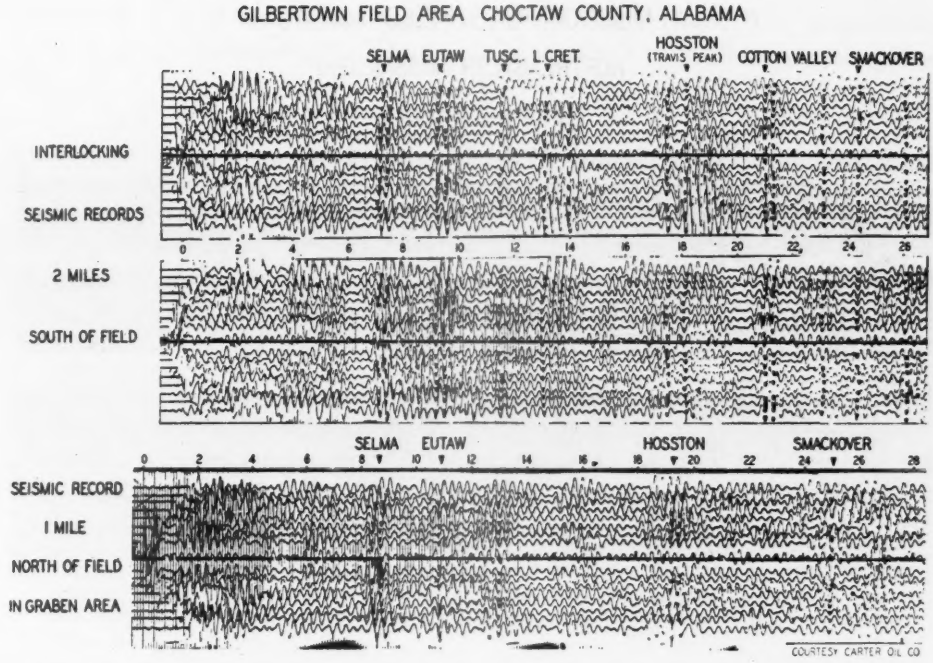

GILBERTOWN FIELD AREA CHOCTAW COUNTY, ALABAMA
SELMA EUTAW TUSC. L.CRET. HOSSTON (TRAVIS PEAK) COTTON VALLEY SMACKOVER
INTERLOCKING SEISMIC RECORDS
2 MILES SOUTH OF FIELD
SELMA EUTAW HOSSTON SMACKOVER
SEISMIC RECORD 1 MILE NORTH OF FIELD IN GRABEN AREA
COURTESY CARTER OIL CO

FIG. 19. Gilbertown Field Area. Choctaw County, Alabama. Interlocking seismic records 2 miles south of field seismic record 1 mile north of field in Graben area. (Courtesy The Carter Oil Co.)

opposite sides of the fault at depths approximating 4,000 feet. Anomalous dips are noted in the major fault zone.

Examples of representative seismic records in the vicinity of the Pollard, Gilbertown, and Muldon fields are shown in Figures 18, 19, and 20. It is evident that usable and correlatable seismic events are present.

Much of the difficulty in obtaining good quality reflection data is attributed to near-surface conditions such as the presence of the Citronelle formation which blankets much of southern Alabama and northwestern Florida, and the limestone outcrops farther east and south in Florida. Seismic reception is also affected adversely by erratic changes in weathering and elevation, and in many instances better quality reflection records appear to be obtained in areas of low elevation. Some success has been reported on the Florida peninsula with the use of multiple geophone and multiple shot hole patterns. The success of future seismic efforts is believed to depend on continued experimenting with consideration of the influence of the mantle rock and other near-surface effects.

CONCLUSIONS

In summary, the recent oil field successes at Pollard and South Carlton indicate the continuing of active development and exploration in southern Alabama.

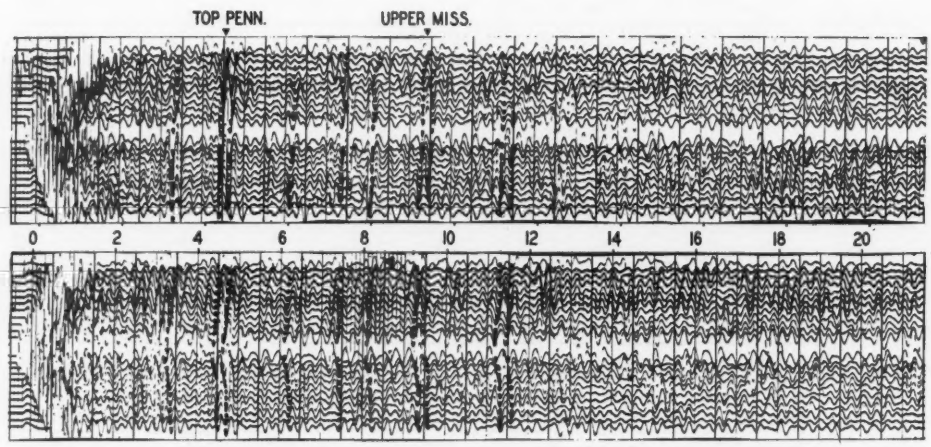


FIG. 20. Muldon gas field area. Northeastern Mississippi. Interlocking seismic records west of gas field. (Courtesy Gulf Refining Co.)

Exploration in Georgia probably has been retarded due to the known relatively thin sedimentary section. Some of the coastal plain sediments in Georgia, however, show characteristics of stratigraphic overlaps resulting from transgressive and regressive seas. Therefore, it is reasonable to expect the existence of favorable strand-line conditions. At the present time a few companies and independent operators are reported planning exploratory programs. In Florida, favorable stratigraphic conditions and the possible presence of structural features favorable to oil accumulation have been recognized for many years. The following paragraph appears in the 1941 A.A.P.G. publication "Possible Future Oil Provinces of the United States and Canada" and warrants quoting at this time, since present exploratory efforts finally are being intensified to attain solutions to the many geophysical problems.

"The progress of exploration in Florida has been retarded by the existence of conditions which make present exploration methods difficult or ineffectual. A covering of Recent materials hampers detailed surface mapping, and the difficulty experienced in obtaining dependable seismic reflections has discouraged this type of work. The value of gravity and magnetic surveys is as yet unknown."

ACKNOWLEDGMENTS

The cooperation from my friends with Gulf Refining Company, The Carter Oil Company, and Seismograph Service Corporation, and the generosity of these companies in releasing pertinent information, has made the presentation of this material possible. The assistance given by Mr. B. W. Blanpied, among many

others who contributed substantially, is sincerely appreciated. The preparation of the illustrations was supervised by C. L. Bury of Seismograph Service Corporation.

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HISTORY OF THE IMOGENE OIL FIELD ATASCOSA COUNTY, TEXAS*

JOHN W. BOLINGER†

ABSTRACT

The original lease block on the area which is now the Imogene Oil Field was taken as a result of the discovery in 1935 by surface geology of a large fault, upthrown to the southeast. A general reconnaissance reflection seismograph survey followed in 1940, preceding the drilling of the discovery well by about two years. A further detailed reflection seismograph survey was made after the discovery to outline the structure more accurately.

The discovery of oil at Imogene was of special interest for it was the first deep Edwards production to be discovered in southwest Texas. Excitement ran high since an entirely new trend was opened and a lease play and exploration program were started that extended across several counties. This was the first of several fields to be discovered along this trend.

The Imogene Field is located in Atascosa County, Texas about 3 miles south of Pleasanton and about 35 miles south of San Antonio. Figure 1 shows the location of the field with respect to other oil fields and the surrounding territory.

This area was mapped by surface geology by H. D. McCallum for Humble Oil & Refining Company in 1935. A fault, upthrown to the southeast, was found (Fig. 2) and the original lease block was taken as a consequence. Credit for this discovery cannot be attributed to geophysical results; but, nonetheless, the reflection seismograph played a very important part in the development of the area.

The first geophysical work done in this area, so far as we can determine, was in 1937, when a gravity survey was made for the Humble Company. The gravity picture (Fig. 3) shows a slight widening of the contours with a small minimum nose where the field is now.

A core drill was introduced into the area in 1938 and nine core holes were drilled. The fault which had been found by surface geology was verified by the results.

The first seismic work in this area was in 1940 when a general reconnaissance reflection survey was conducted by the Humble Company. This survey was designed to cover the area as rapidly as was practical. Instead of continuous profiling, holes were "spotted" along the roads at intervals of a mile or more. A dependable picture resulted in this manner because of the definite character of a reflection (Fig. 4) which comes in consistently in this area and can be reliably correlated over long distances. This reflection comes from near the top of the

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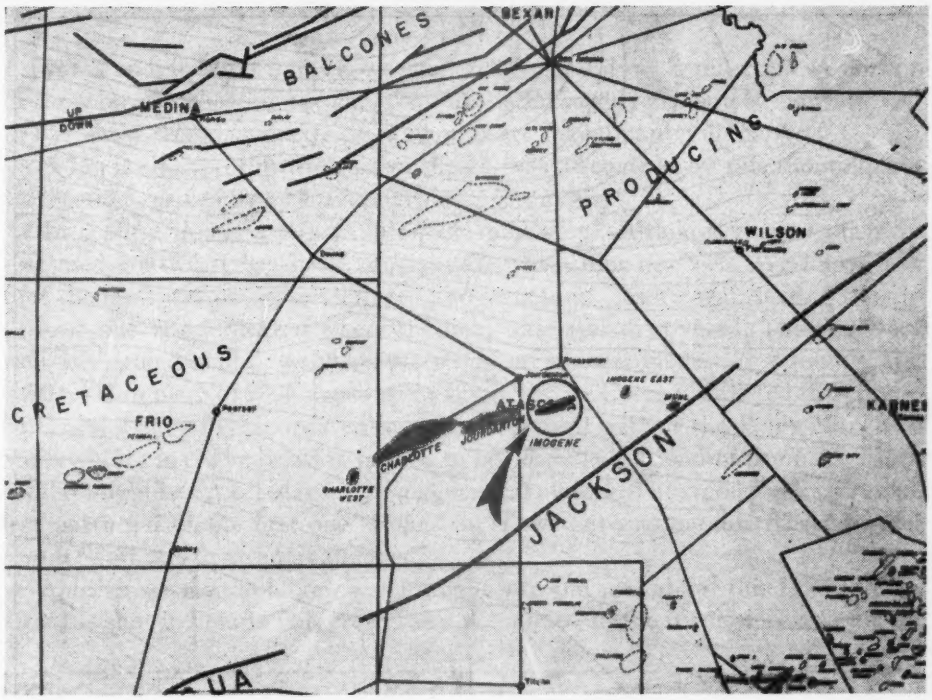

FIG. 1. Map showing the location of Imogene Oil Field at Ascosa Co., Texas.

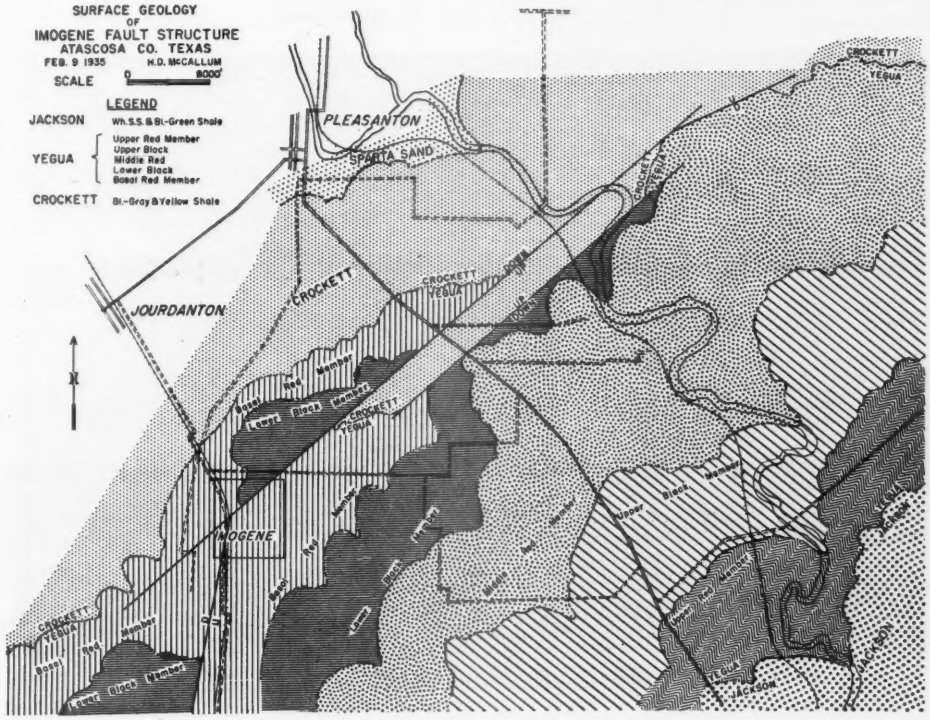

FIG. 2.

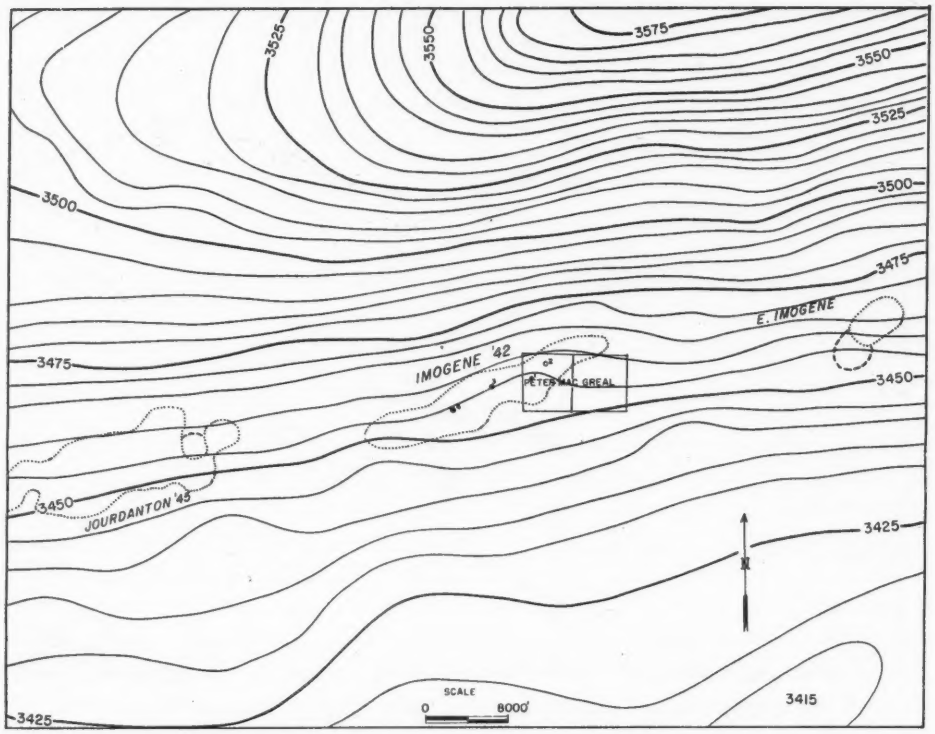

FIG. 3. Gravity map of the Imogene oil field.

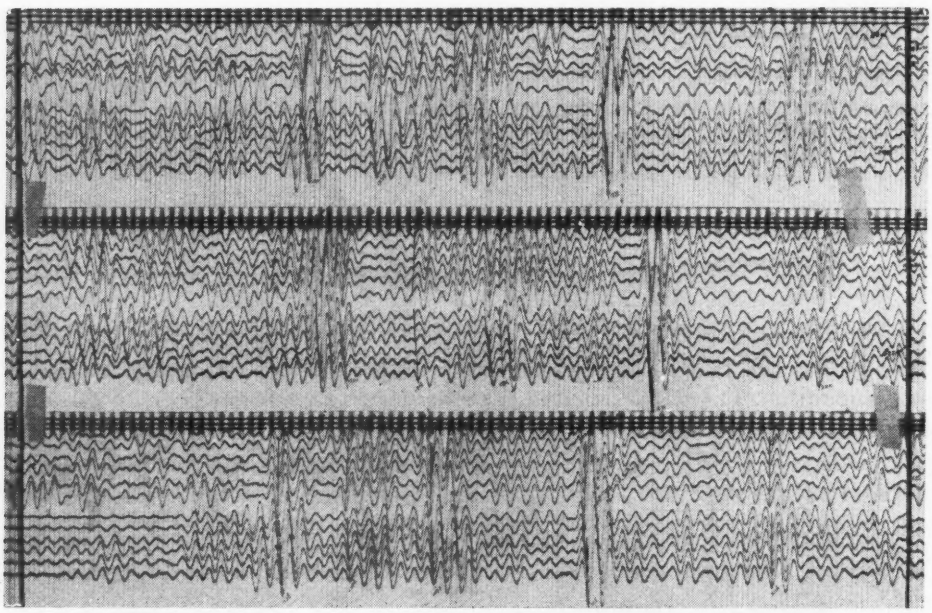

FIG. 4. Typical seismograms of Imogene Area shot in 1940.

Edwards and, in what follows, we shall call it the Edwards reflection. A portion of three records showing the character of the Edwards reflection is shown in Figure 4. These records, selected at random, were taken many miles apart.

A big fault, upthrown to the southeast, was discovered by this shooting and was further verified by a continuous profile line across it.

In a sense this is a remarkable picture (Fig. 5). Although made from very scattered control it has been substantiated exceptionally well. We know now that the fault was accurately located and structural closure against it on the upthrown side was indicated where the field was later discovered. The discovery well was drilled about two years after this survey was made.

The Humble No. 1 Thompson, the discovery well, was completed in September 1942. This well was located in the east central part of the Peter MacGreal Survey No. 1293. The location proved to be near the east end of the field, which is what might be expected from the geophysical picture. The second well was 2,000 feet northeast of the first one. It had oil shows but was too near the oil-water contact and was dry and abandoned.

Another seismograph crew was brought into the area about this time and the area was shot in detail. This crew was not confined to the roads since a bulldozer

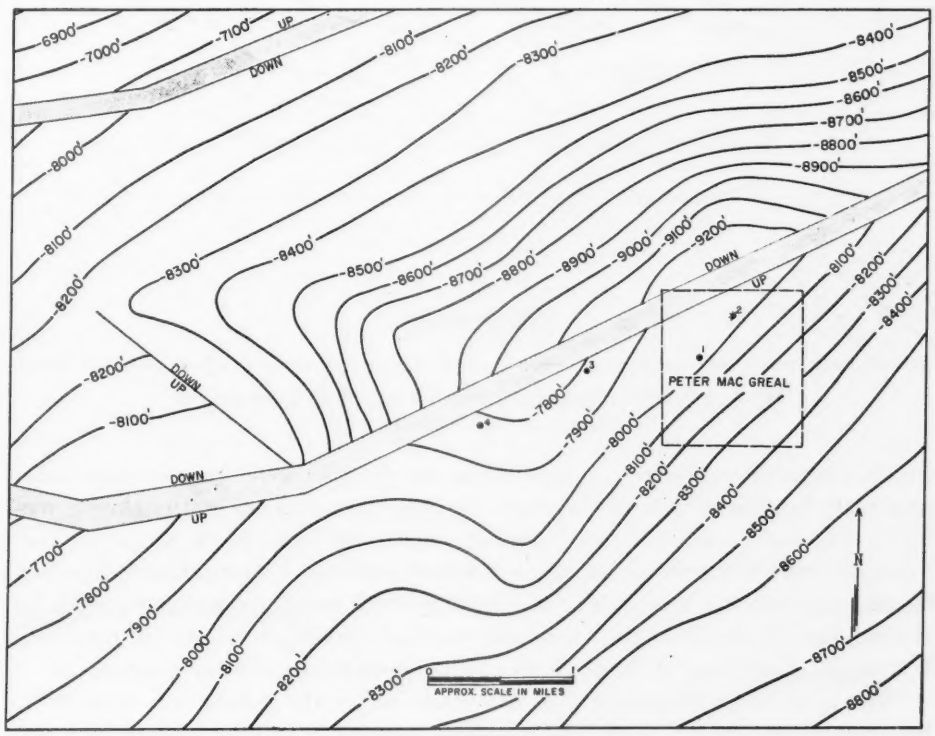

FIG. 5. Reflection seismograph reconnaissance map based on 1940 data.

served to cut lines through the thick Mesquite brush which covers that country. This made it possible to shoot lines almost anywhere considered desirable.

The detailed pictures (Fig. 6 and 7) show the main up-to-the-coast fault in almost exactly the same place as in the original reconnaissance picture, but additionally much minor faulting was found with this close control. The interpretation shown in Figure 6 was made in the field office as the shooting progressed. The interpretation shown in Figure 7 is the better and final interpretation of the area

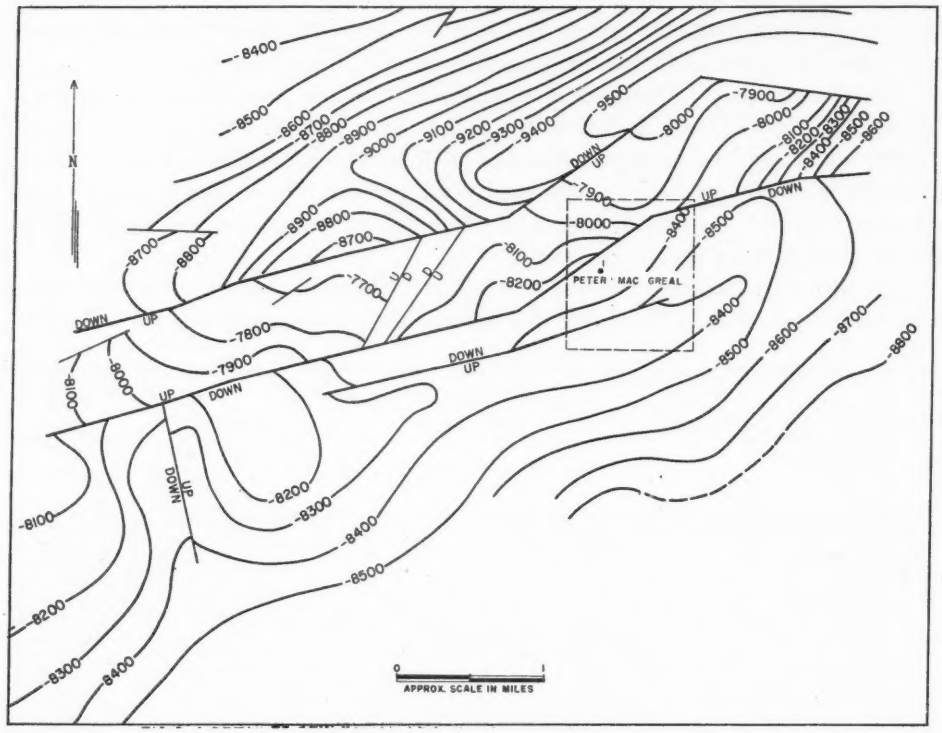

FIG. 6. A detailed reflection seismograph map of the Imogene Area. Made in the field office in 1942.

which was made in the home office. These two pictures were made entirely independently but the quality of the data is so good that they are in very close agreement. The main fault is shown in almost exactly the same place in the two pictures and most of the minor faulting is similarly portrayed. Accurate velocity data for this area were not available at the time the work was done, which accounts for the fact that the depth of the Edwards is shown to be deeper in both pictures than it really is. The throw of the faults is also exaggerated for the same reason.

The location for the third well was made before the survey was completed, but enough geophysical work had been done to assist in making the new location. This well was too near the fault and was dry. The fourth well was better located and made a good producer.

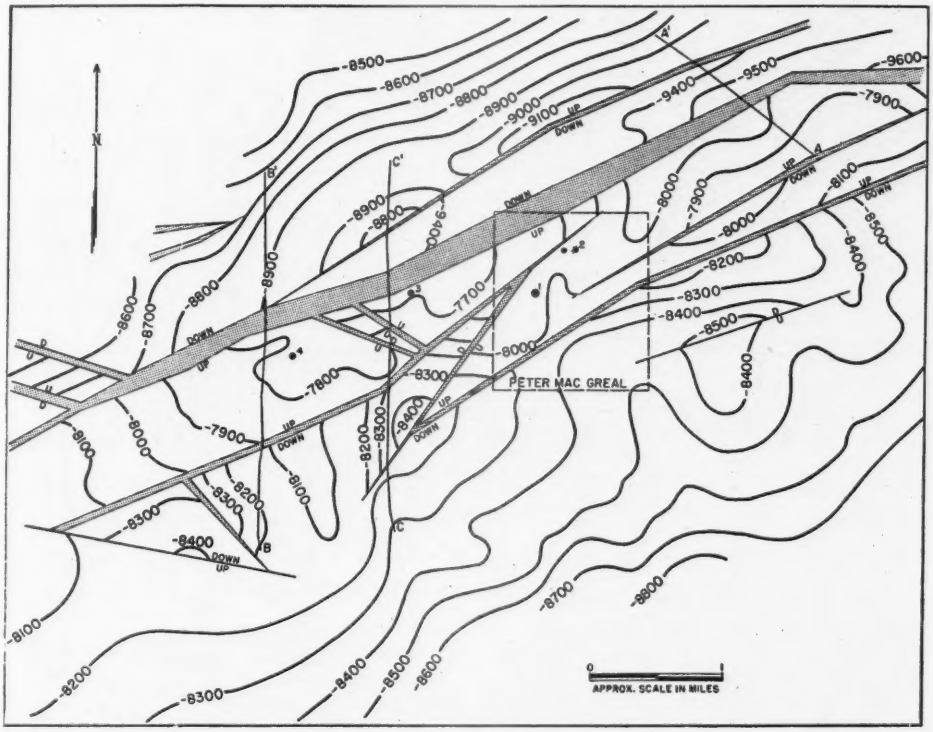

FIG. 7. The final interpretation of the detailed reflection seismograph survey of 1942.

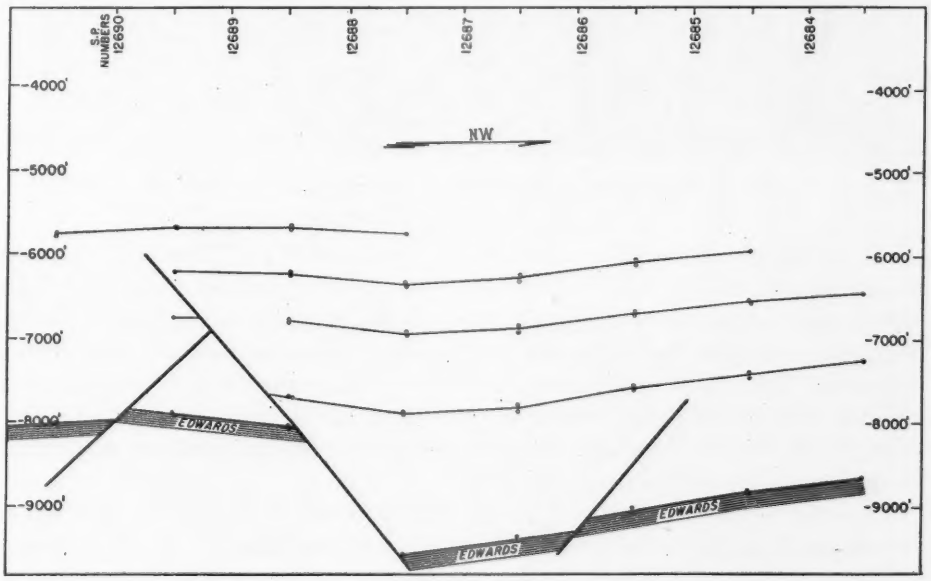

FIG. 8. A seismograph cross section A-A' (Fig. 7) Imogene Area.

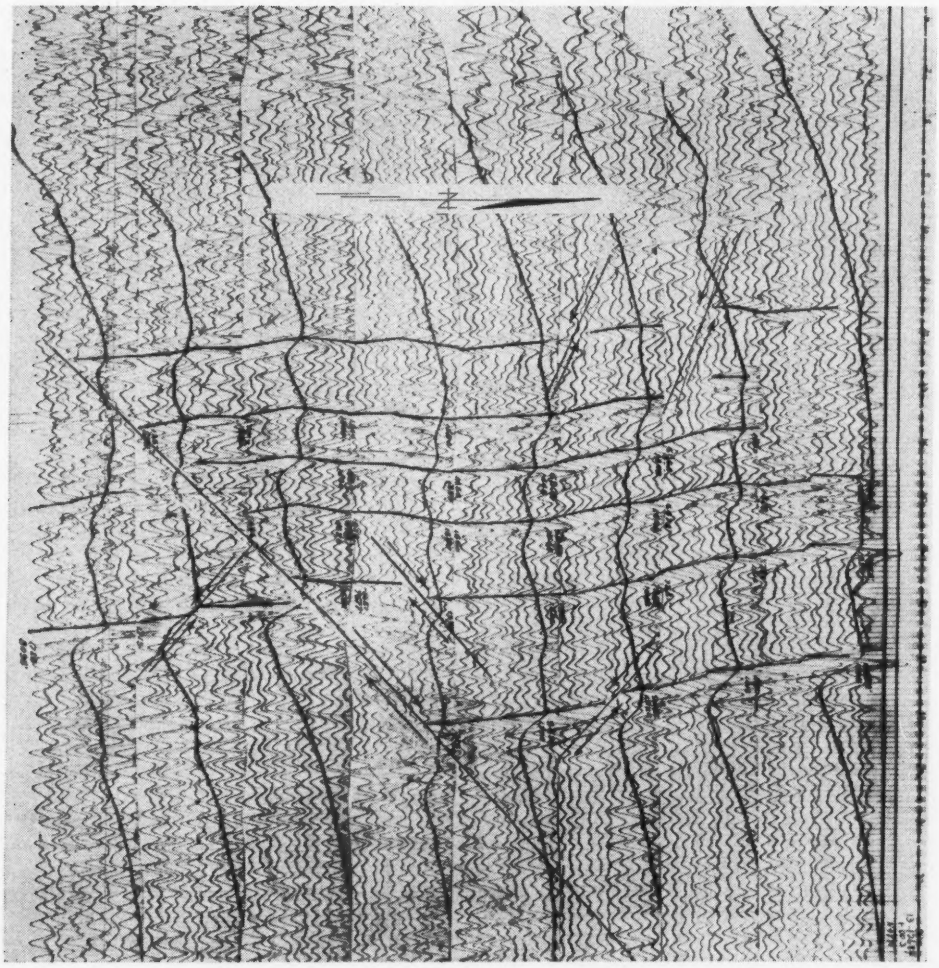

FIG. 9. The seismograms used in preparing cross section in Figure 8.

A section of the Imogene area is shown in Figure 8. It shows, from north to south, a small fault in the Edwards which does not cut the upper beds, the main up-to-the-coast fault which cuts the Edwards and the beds above, thereby determining the hade of the fault, and another small down-to-the-coast fault in the Edwards. The records from which the section was made are shown in Figure 9 and the sequence of events shown on the section can be easily traced on the records. These records have been trimmed and fitted together in an effort to make it appear as one continuous record.

Another section across the Imogene field is shown in Figure 10. Here again we see the main up-to-the-coast fault followed by a small fault in the other direc-

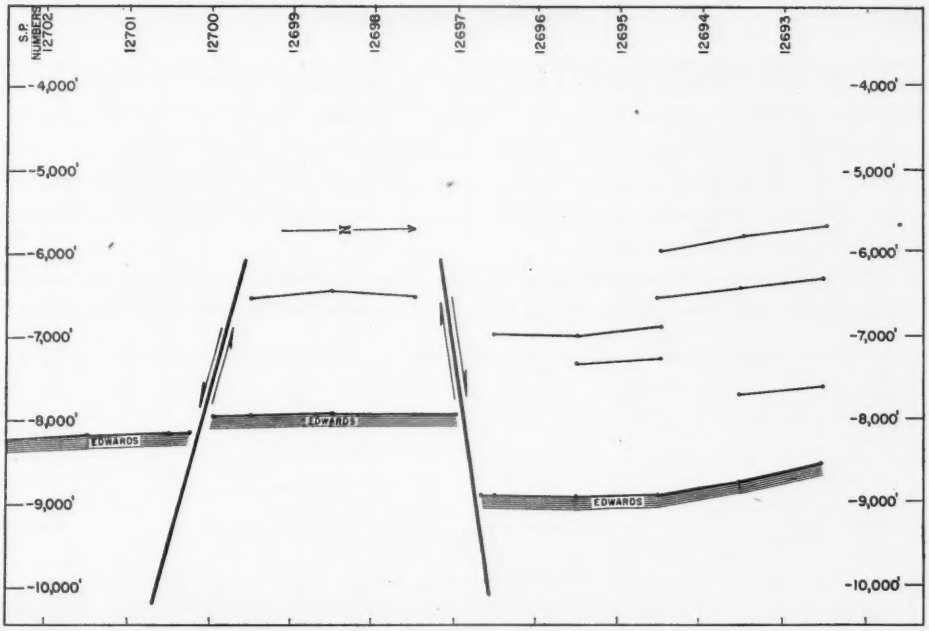

FIG. 10. Seismograph cross section B-B′ (Fig. 7) Imogene Area.

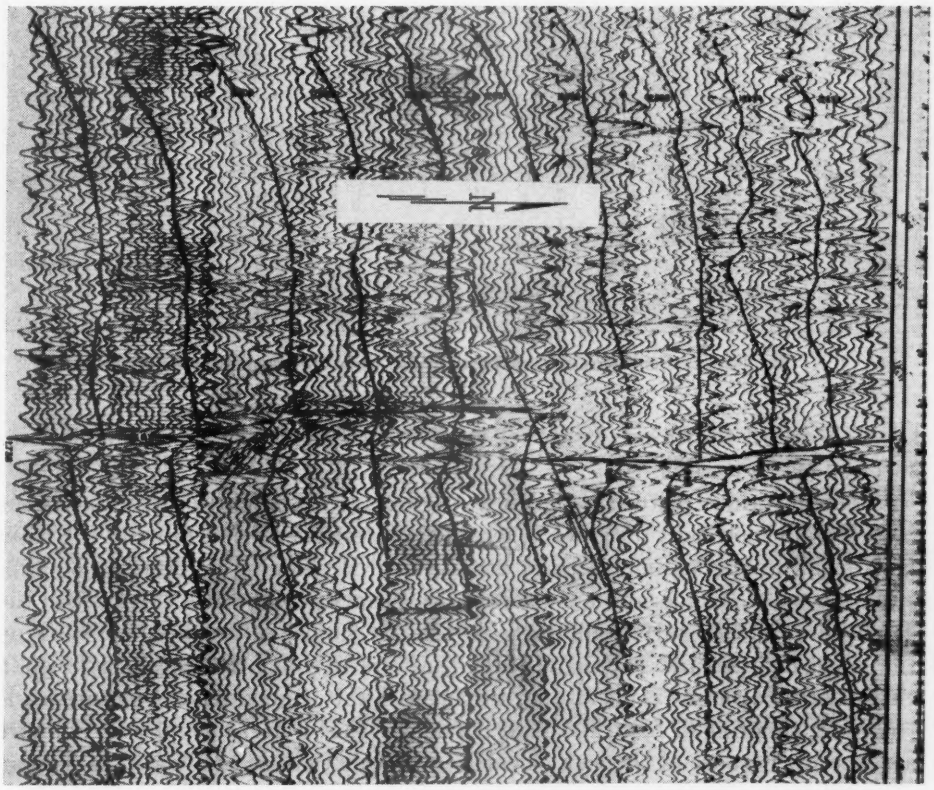

FIG. 11. The seismograms used in preparing cross section in Fig. 10.

tion. The records from which it was made are shown in Figure 11. This section was selected for a special reason. The smaller fault has not yet been found geologically although wells have been drilled on both sides of it. Nonetheless, it appears plainly on the seismic section. It is a good example to show that faults may be found from good seismic data though difficult to locate by subsurface methods without very close control.

Another section across Imogene field is shown in Figure 12. This is one of the most highly faulted sections in the area. The records are shown in Figure 13 and

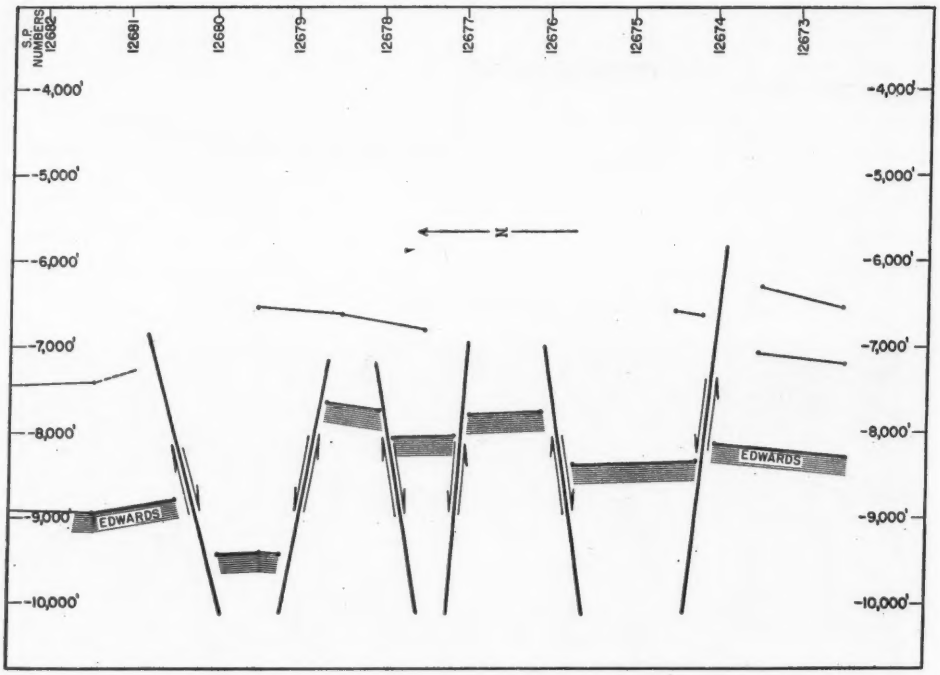

FIG. 12. Seismograph cross section C-C′ (Fig. 7) Imogene Area.

all of the faults shown on the section may be very easily detected by a close inspection of the records.

The subsurface picture is shown in Figure 14. A comparison of the various pictures will show that there is remarkable agreement in the location of the main fault in all of the seismic pictures and its final location as determined by subsurface control. The location of the fault by surface geology also checks with the geophysical and subsurface pictures, though the minor faulting does not show on the subsurface picture. The shape of the contours on top of the Edwards shown in the subsurface picture is in close agreement with the original seismic picture made from spot shooting in 1940, although the depths shown in the geophysical picture are in error because of the lack of velocity information, as previously explained.

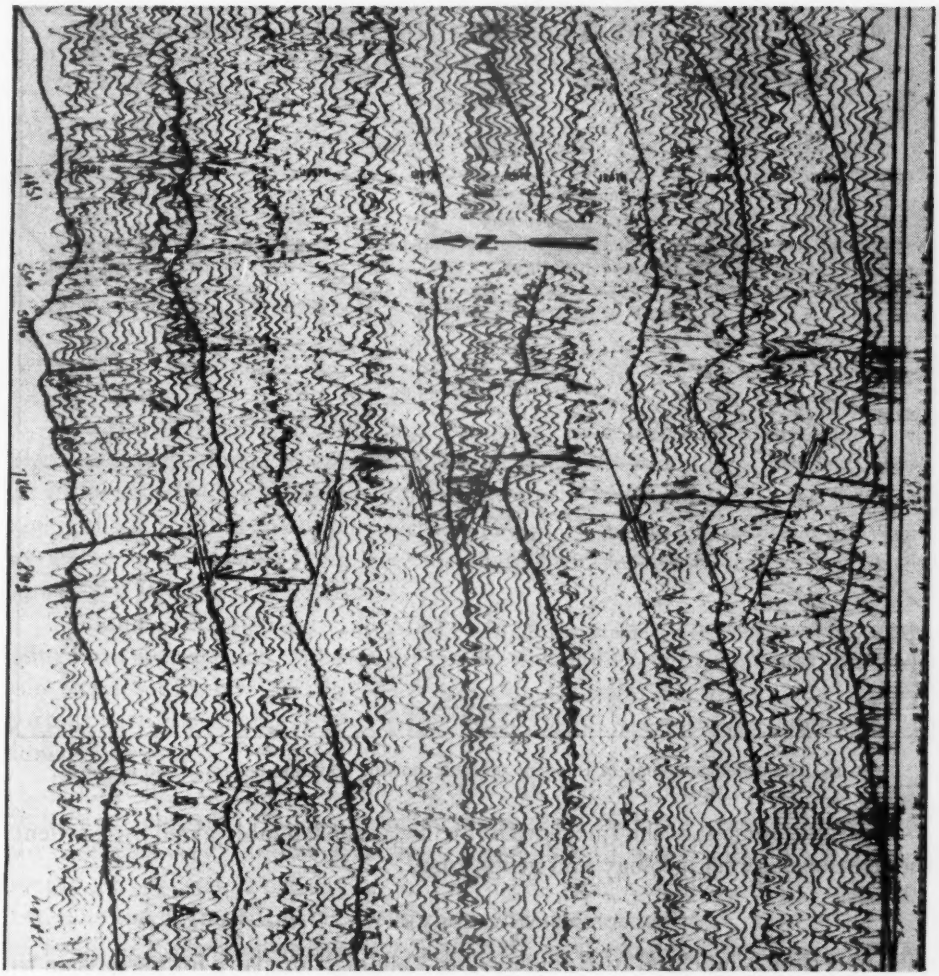

FIG. 13. The seismograms used in preparing cross section in Figure 12.

This field is not a very large one. Drilling in the field has been on 40-acre spacing since its discovery. A total of 38 wells have been drilled to the Edwards in this area and about the same number of depth points were used in making the first seismic picture, but approximately 250 depth points were used in making the detailed picture. It is highly probable that if enough wells were available most of the faults found geophysically would be detected.

All of the production in this area was in the Edwards limestone until June of 1951 when shallow oil was discovered in a Carrizo Sand by Martin, Shelly, and Thomas. This is known as South Imogene since these wells are some distance south of the old field. This trap is on the same fault, however, that determines the production in the older field.

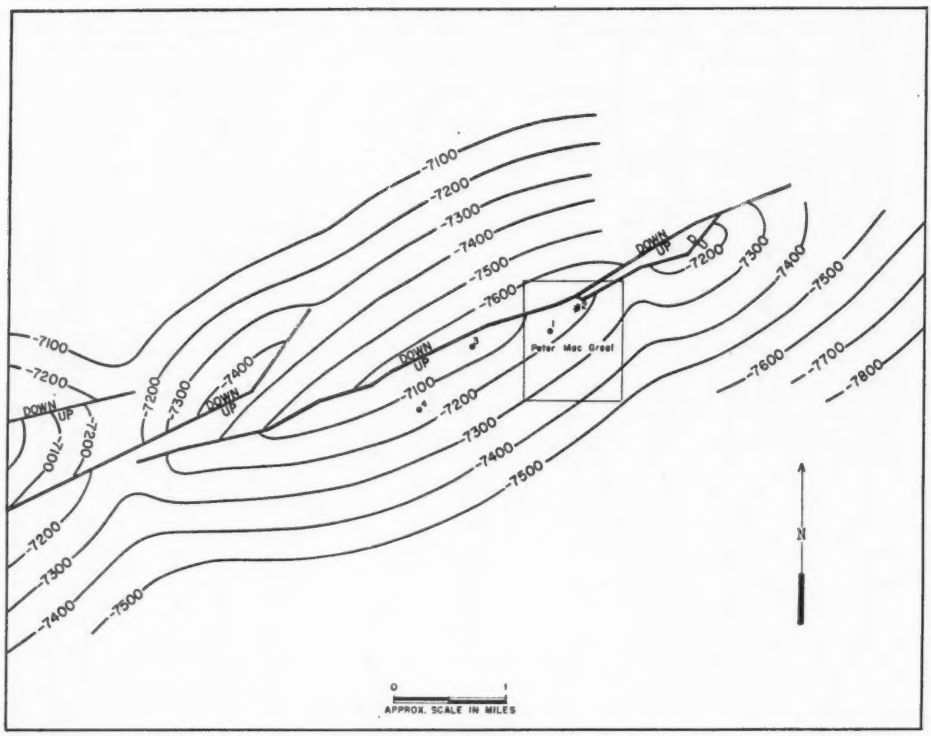

FIG. 14. The subsurface map of Imogene oil field showing contours on top of the Edwards.

The development of the Imogene Oil Field was considerably aided by excellent cooperation between geology and geophysics.

ACKNOWLEDGMENTS

The writer is indebted to Humble Oil & Refining Company for permission to publish this paper; to Mr. L. H. Gates and Dr. M. M. Slotnick for helpful advice and suggestions; to Mr. H. D. McCallum and to Mrs. J. H. Story for geologic information; to many colleagues who have worked on this area; and to Mr. J. D. Johnston for preparing the illustrations.

THE GEOPHYSICAL DISCOVERY AND DEVELOPMENT OF THE BAYOU COUBA DOME*

LOUIS F. MELCHIOR†

ABSTRACT

This case history of the Bayou Couba Dome, St. Charles Parish, Louisiana, reports the results of seismic refraction, seismic reflection, and gravity exploration leading to the discovery of the dome. These data, together with the results of additional exploration done to define the dome, compare favorably with the actual dome shape to the extent it is determined by drilling.

INTRODUCTION

The Bayou Couba (North Lake Salvador) Salt Dome, a moderately deep piercement-type dome, is centered in the northeastern part of irregular section 13, T15S-R21E, St. Charles Parish, Louisiana, on the north shore of Lake Salvador and is about 15 miles SW of New Orleans (Fig. 1). The terrain, where not covered by water, is mostly low-lying level marshland which gives no expression of the subsurface structural anomaly.

The dome was discovered in March, 1928, with the refraction seismograph, using fan-type shooting. Subsequent application of different geophysical methods and techniques shows, in the case of this dome, that the art has played an important part in outlining it and in developing the oil reserves associated with the domal structure.

The discovery well on this dome, the Gulf Refining Company No. 1 Delta Securities Company, Inc., was started on July 13, 1942 (14 years after the geophysical discovery), and completed on September 19, 1942, with an initial production of 374 barrels per day of 36° gravity oil from a sand section at 6,530–40 feet. The top of the salt in this well was found at 6,898 feet.

Prior to the commencement date of drilling, a refraction seismograph fan-type shooting survey was made in March, 1928; a gravity reconnaissance survey with pendulum and gravimeter was carried out in September, 1935, and July, 1936, respectively; and a detailed gravimeter survey, a reflection seismograph survey, and some more refraction shooting were accomplished simultaneously during the period November, 1941, to January, 1942. Subsequent to this same date, radial refraction surveys were shot in March and April, 1943, and in March and April, 1945. Altogether 8 different geophysical investigations were made—3 by gravity, 5 by seismograph.

Development of the petroleum potentialities shows a monthly production rate for July, 1951, of 47,045 barrels and an accumulative production of 2,097,007 barrels as of July 31, 1951.

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GEOPHYSICAL PROCEDURE AND RESULTS

The initial geophysical program in March, 1928, which resulted in the discovery of this dome was carried out using the refraction method of fan-type shooting. The shot point and geophone layout (Fig. 2) illustrates very clearly the limitations on early geophysical prospecting, when equipment such as the marsh buggy and helicopter was not yet available for transportation. It is notable that all of the geophone locations are in the water and that, although the shot points are on the marshland, they are within easy portage distance of the waterways.

The survey consisted of six shot points from which shooting took place to sixty-three geophone locations. Time leads were observed on fourteen of the records procured, and the location of the dome as ascertained from these leads is shown by the circular cross-hatched area centered along the east range line of T15S-R21E. The center of the dome as revealed by drilling also is marked on this map to show how accurately this early work had located the anomaly.

In passing, it is of interest to note with reference to Figure 1 that the westernmost shot point in T15S-R20E was located approximately over the top of the Bayou Des Allemands Dome and that the southeasternmost geophone locations in southcentral Lake Salvador were over the Lake Salvador Dome. However, it

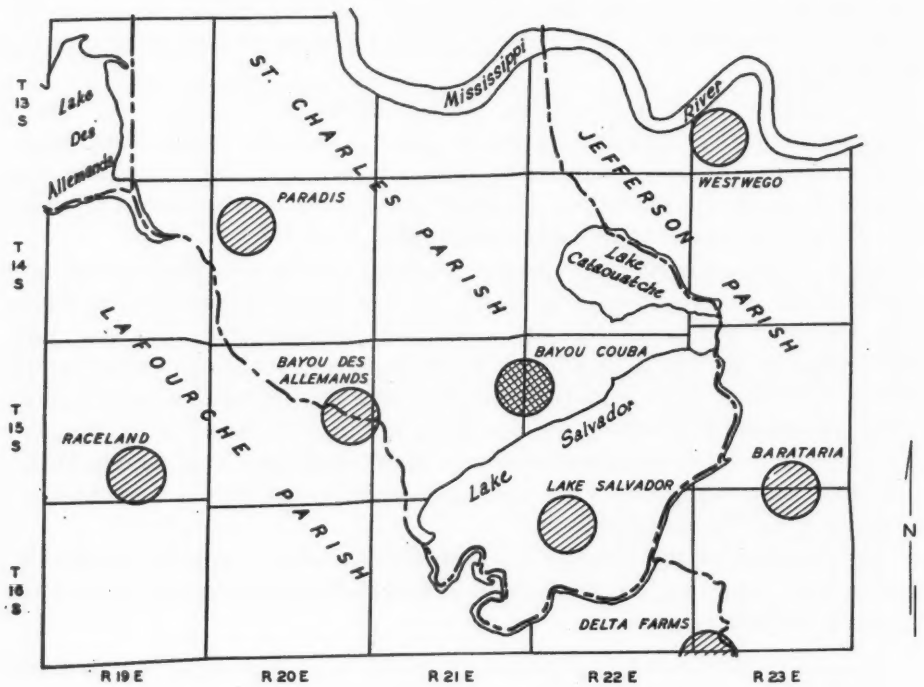

FIG. 1. Location of Bayou Couba Salt Dome in southern Louisiana.

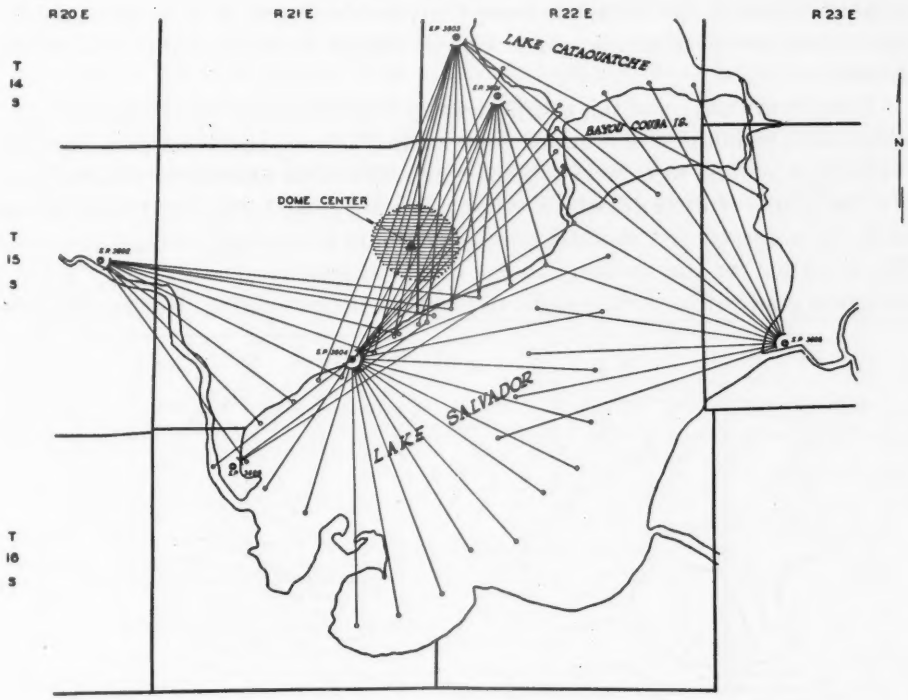

FIG. 2. Shot point and geophone layout of initial refraction fans over Bayou Couba Dome.

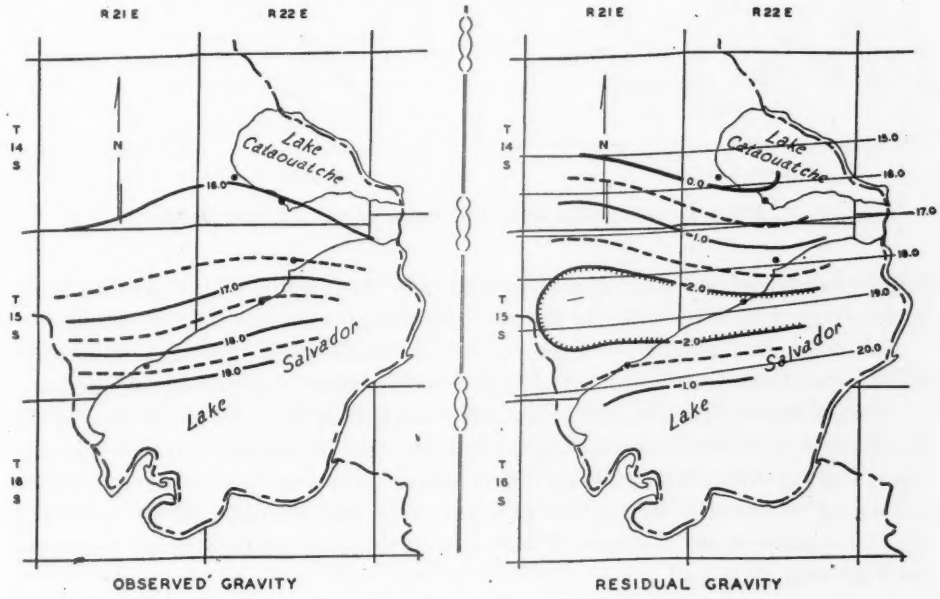

FIG. 3. Original gravity measurements over Bayou Couba Dome.

should be pointed out in this instance that, for the length of shot-geophone distance used, the penetration was not great enough to detect these two nearby domes.

Further evaluation of this prospect was not attempted until September, 1935, when two pendulum observations were made. In July, 1936, the data obtained from the pendulum work were supplemented with three gravimeter observations.

The results of these gravity measurements are given by Figure 3 which shows both the observed and residual gravity contours at one-half milligal intervals. The evidence for the anomaly in the observed gravity shows as only a small change in gradient to reveal a slight terracing in the contouring. However, a quite

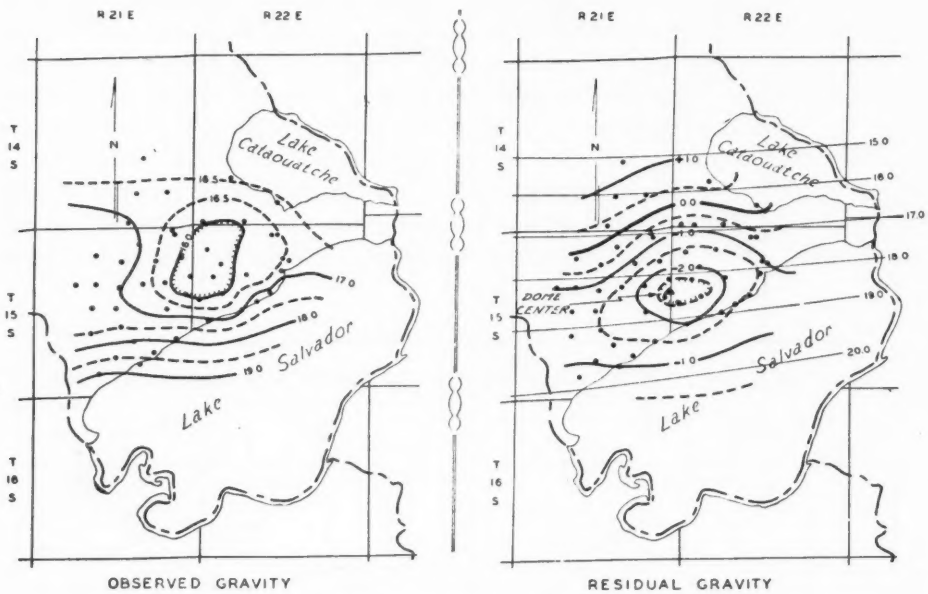

FIG. 4. Gravity results of detailed survey of Bayou Couba Dome.

definite east-west elongated minimum results in the residual picture when a fairly uniform regional, shown by the smooth one-milligal contours, is subtracted.

Although this work pointed to anomalous conditions in the area, it was not satisfactory from the standpoint of further localizing or pinpointing the anomaly.

The additional geophysical exploratory work done prior to the drilling of the discovery well was accomplished in the interim from November, 1941, to January, 1942. During this period, a detailed gravimeter survey and a seismograph survey consisting of seven reflection profiles, one refraction profile, and six refraction arcs were made simultaneously. The results of these investigations are portrayed by Figures 4, 5, 6, and 7.

In Figure 4, which shows the observed and residual gravity results from the

detailed survey with one-half milligal contours, the presence of anomaly, represented by a strong minimum, is outstanding in both pictures. Also, it is seen that the center of the dome known from subsequent drilling falls within the smallest closing contour on the residual gravity minimum.

Attention is called here to the density of gravimeter stations in comparison to the previous coverage in the first gravity work. Forty-five stations were added in the anomalous area to give the control shown. These additional observations

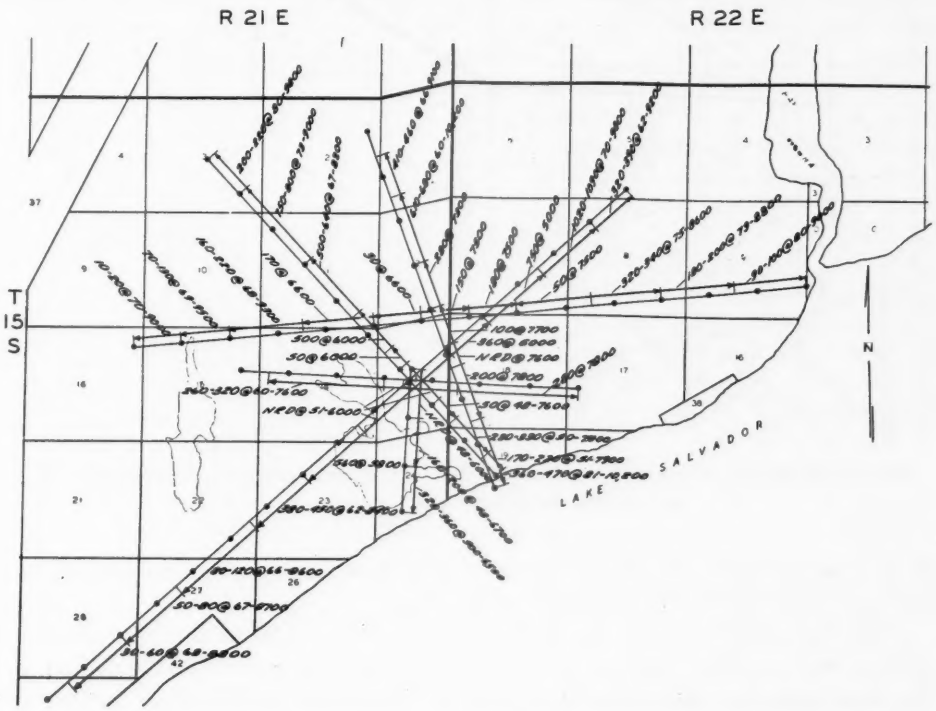

FIG. 5. Component dip rates determined by reflection profiles over Bayou Couba Dome.

and the supplementary seismograph coverage, on which a discussion will follow, would have been impossible without the expenditure of considerable time, labor, and capital had it not been for the advent of the "marsh buggy."

Figure 5 shows the interpretation results of the reflection seismograph records to give the component dip rates at the depths noted. These components show dip away from a central area of little or no dip, defined on four profiles crossing it, in Section 13, T15S-R21E. In general, the records obtained were sufficiently reliable to show the approximate magnitude of dip; but it was not possible to correlate positively the reflected energies to ascertain the exact amounts of dip nor to be certain of the many fault suggestions indicated on the poor and questionable records by abnormally steep reflected energy and/or absence of reflected energy.

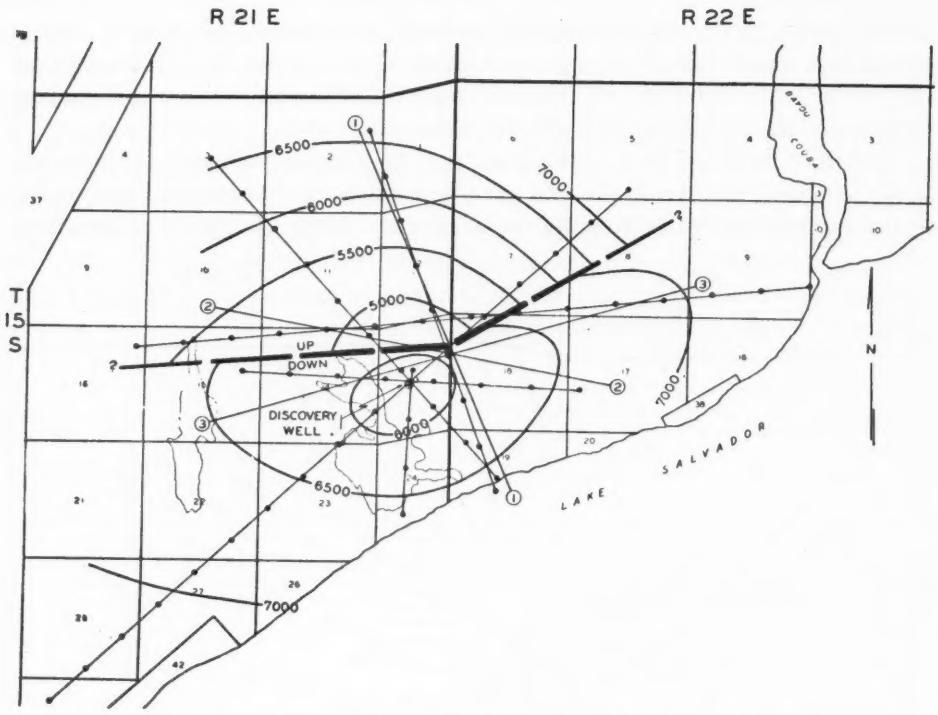

FIG. 6. Generalized contour map based on reflection dips. Contour values are subsea. Location of first well shown near center of section 13.

As a consequence, it was impossible to develop an accurate structural picture depicting a suspected complex pattern of faulting.

This fact, however, did not prohibit or deter the construction of a contour picture, with a certain amount of tolerance, to show the general configuration of the dome and the most probable alignment of the more definite fault evidences. Figure 6 shows the picture, so developed, to be one of an east-west elongated domal uplift which is traversed by a fault downthrown to the south and trending to the west and to the northeast from the approximate center of the uplift. The magnitude of fault is arbitrary; however, the depth values of the contours are supported by the depth to the deepest reflections in the area of no dip that were thought to be reliable and by the fact that calculations from the refraction shooting results showed sediments might exist to a minimum depth of 5,500 feet. These calculations were based on an approximated sedimentary velocity distribution, $V_i = V_0 + KZ$, where $V_0 = 5{,}740$ feet per second and $K = 0.5$.

The results from the additional refraction shooting done in conjunction with the reflection shooting are shown by Figure 7. The shot point for the arc shooting was located in the southwest quarter of Section 10, T15S-R22E, where Bayou Couba enters Lake Salvador, and the shot point for the profile shooting was

situated in the northwest quarter of Section 33, T15S-R21E, at the southwest end of the profile. The time leads illustrated graphically on this map were computed as the differences between the observed refracted first arrivals times and the normal refracted times for the shot-detector distance involved on the basis of the sedimentary velocity distribution noted in the preceding paragraph. However, since the date of this shooting, additional velocity control obtained in conjunction with radial refraction surveys has shown the velocity distribution to

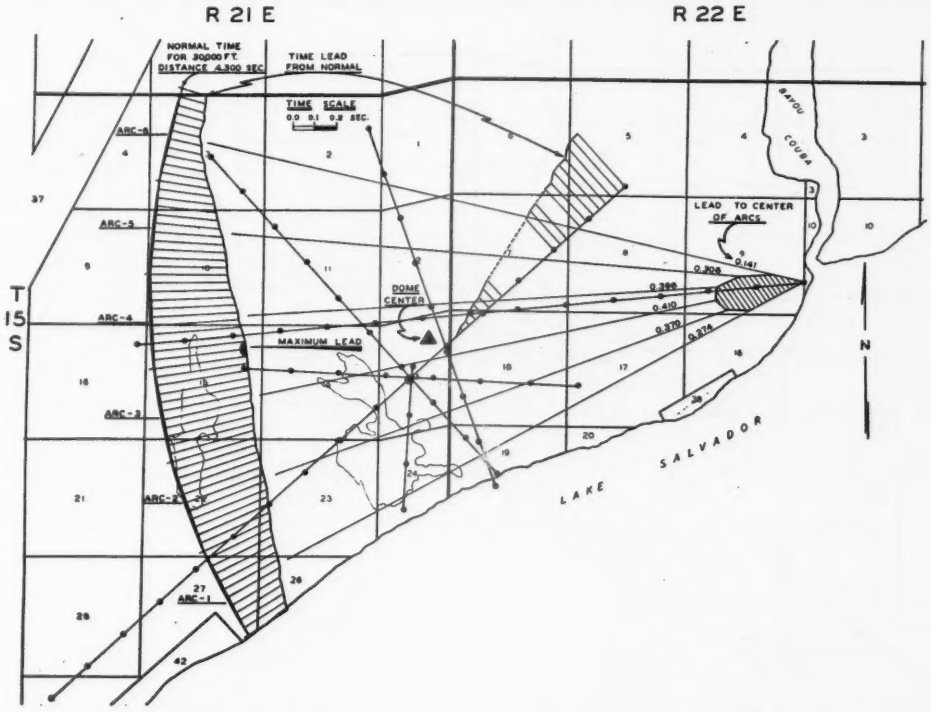

FIG. 7. Results of additional refraction survey done in conjunction with the reflection shooting.

approximate more appropriately conditions where $V_0 = 5{,}740$ feet per second and $K = 0.6$ for the sedimentary section. We now know because of this additional velocity information that the time leads shown in Figure 7 should be reduced by about 0.200 second. Also, it can be computed now, with the shape and depth of the dome known from drilling, that if the corrected time leads are to be satisfied, the minimum travel path through salt must be about 3,000 feet when the more appropriate velocity distribution is used. It does not appear that the early refracted arrivals are chargeable to an increase in the sedimentary velocities over the dome in view of the velocity control now available.

After the report on this seismograph survey was submitted, a well was drilled as noted in Figure 6 near the center of Section 13, T15S-R21E, to test the petro-

leum possibilities of the prospect. This well was completed as a producer with an initial production of 374 barrels per day of 36° gravity oil from a sand section at 6,530–40 feet. The top of the salt in this well was found at 6,898 feet. This fact was quite gratifying in light of an estimation based on the seismograph work that salt probably would not be drilled at a depth of less than 6,000 feet. The shallowest depth of salt drilled to date is 6,294 feet in the northeast quarter of the same section.

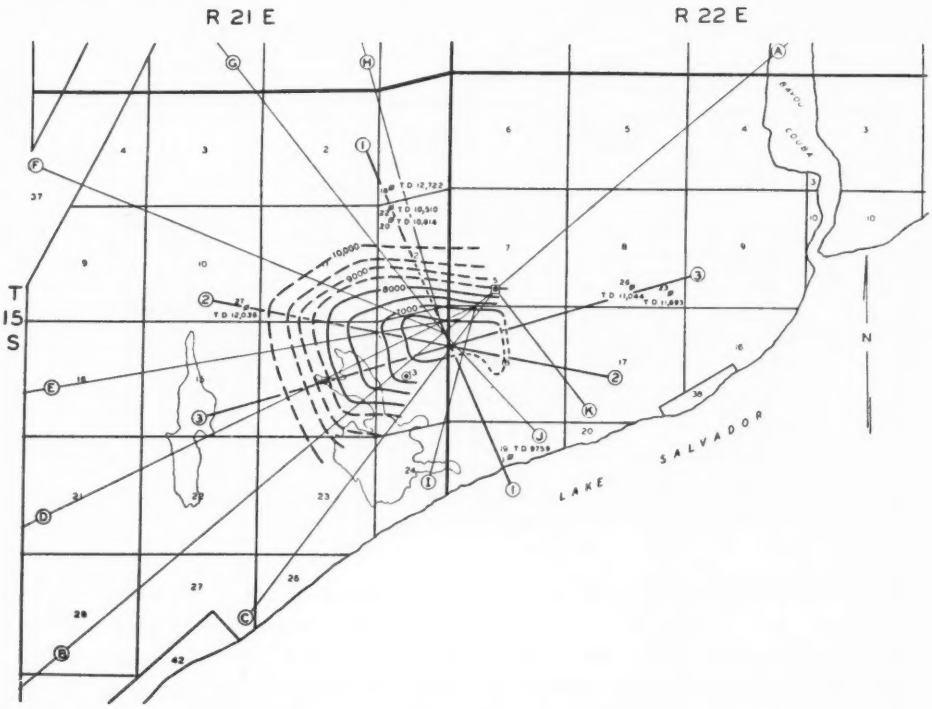

FIG. 8. Results of radial refraction survey, with geophones placed in Well No. 5.

Additional drilling was carried on, and when two more producers and two dry holes had been completed, it was decided to shoot a radial refraction survey, Figure 8, with geophones in Well No. 5 on the northeast flank of the dome, to outline further the size and shape of the dome material. As two geophones, separated by 1,000 feet, were lowered into the well, shots were fired from shot points along Profile "A," northeast from the well, to ascertain sedimentary travel times for the development of a wave front chart. Subsequent to this shooting, with the lower geophone in salt just below 8,400 feet, shots were made along ten radial profiles, "B" to "K," for the purpose of outlining the dome material. The interpretation of the data obtained is shown by the 500-foot contours picturing the outline of the dome material. Profiles 1, 2, and 3, and the outpost wells, which did not reach salt, also shown, will be discussed later.

After these seismograph results were reported, drilling was continued; and, when the fourteenth well had been drilled, plans for another radial survey were made. Shooting this time, as shown by Figure 9, was to a geophone in sediments approximately 50 feet above the top of the anhydrite caprock at a depth of 10,504 feet in Well No. 14 on the southeast flank of the dome. The shooting procedure on this project was the same as on the first radial survey, and this figure shows the sedimentary control Profile "A" and ten other profiles, "B" to "K," Profile "G" excepted, used to outline the dome material. The contoured results on the

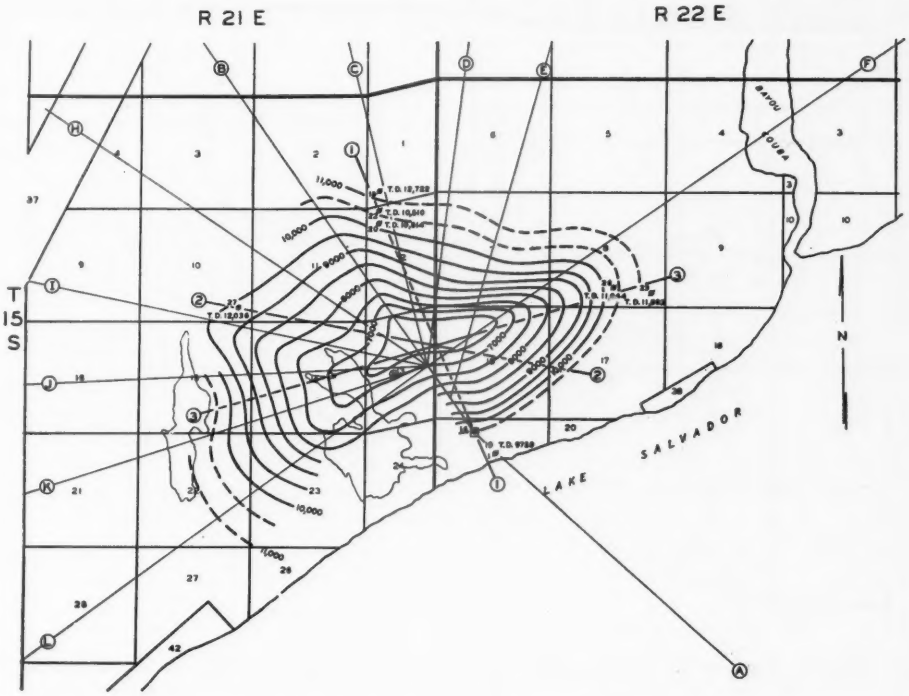

FIG. 9. Results of additional radial refraction survey, with geophones placed in Well No. 14.

dome material are mapped by 500-foot contours which show the dome to be elongated considerably in the northeast-southwest direction. It is interesting to note how this picture compares with the sedimentary picture, Figure 6, which shows a similar distortion. As in the case of Figure 8, the numbered profiles and outpost wells will be discussed later.

Figure 10 shows the 500-foot contours, the 6,300-foot closing contour excepted, on the dome material as determined from the well calls; the total depths in the outpost wells; and the numbered profiles, noted previously, along which comparisons are made in Figure 11.

In Figure 11, the dome cross sections along Profiles 1, 2, 3, and the limit-

ing factors of the deep outpost wells are compared with the results from the reflection survey and the two radial refraction surveys. At a first glance, one could be very critical of this comparison and state that the agreement between the dome outlines from the radial surveys and the actual dome outline from drilling is not very good. However, when the possibilities for discrepancies are considered, the criticism might not be quite so strong. Discrepancies result at

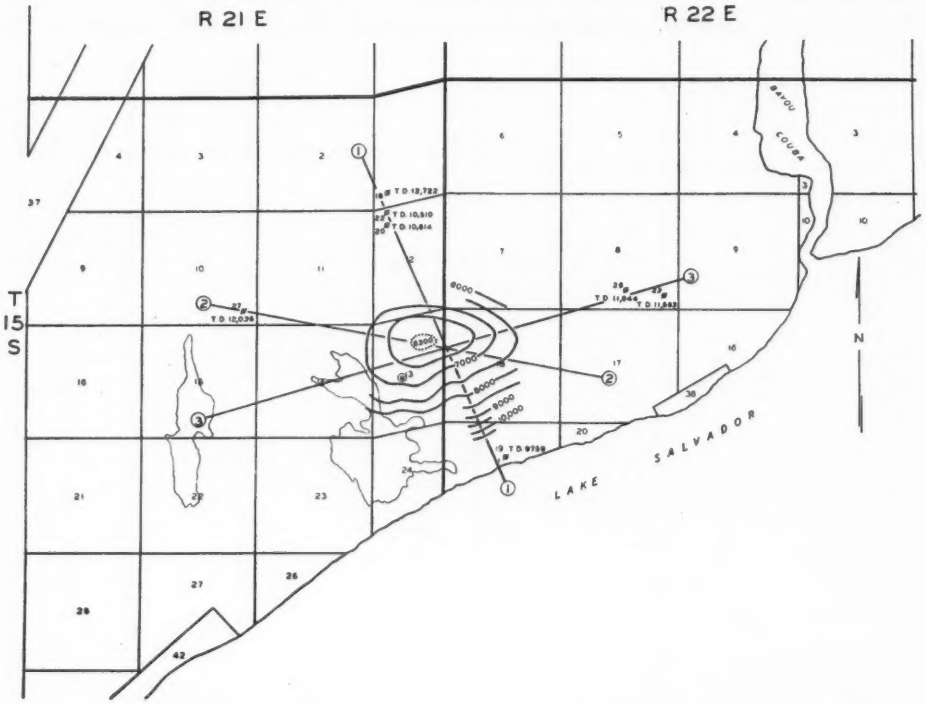

FIG. 10. Contours on dome material as determined by limiting well information as shown.

present from the facts that the sedimentary velocities may not be accurately determined near and below the depth of the detector, that the geophone was not in dome material, and that an unknown amount of caprock or anhydrite may be present on the dome flanks.

Probably most outstanding is the fact that the dome is shown generally to be too large by the second survey as compared with the size shown by both the first radial survey and drilling. The cause of the difference is most probably chargeable to not assuming a great enough thickness for the caprock (anhydrite) drilled at the bottom of Well No. 14 where the geophone was located. The effect from assuming a greater thickness of anhydrite, in general, would have been to decrease the dome size; but, in particular, it would have been to decrease the size more at depth where an appreciable amount of flare is shown and where sediments are

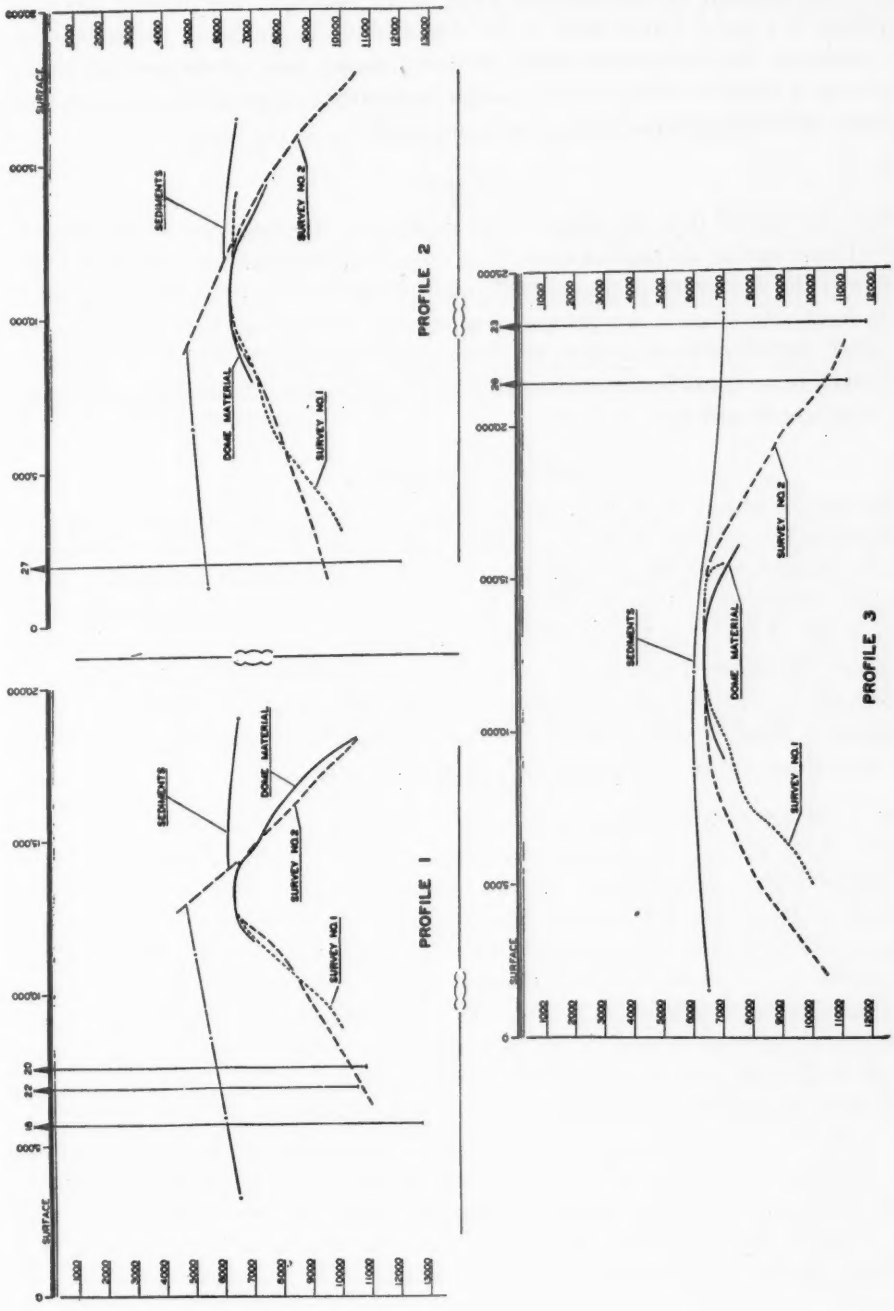

FIG. 11. Available well information compared with results of the reflection survey and the two radial refraction surveys.

shown to be present by the outpost wells. Unfortunately, the drilling has not progressed to a point where more of the dome would be outlined, the southeast flank excluded, to give a more complete comparison. Also, at the present time, there is not a resolved sedimentary geologic interpretation available to which the reflection seismograph results may be compared.

CONCLUSIONS

With the fact of this case history now presented, the discovery of the Bayou Couba Dome can be accredited alone to geophysical explorations. The first well, which was the discovery producer well, was located on the basis of geophysical results from refraction and reflection seismograph surveys and gravity surveys. Moreover, radial refraction surveys subsequent to the completion of the discovery well have contributed appreciably to the definition of the dome material as to both depth and size.

ACKNOWLEDGMENTS

The writer wishes to express appreciation to the executives of the Gulf Oil Corporation for release of the data used and to Dr. Leo J. Peters, Division Director, Geophysical Operations, to Dr. E. A. Eckhardt, Vice-President and Associate Director, and to Dr. Paul D. Foote, Executive Vice-President and Director, all of the Gulf Research and Development Company, for permission to publish this paper. The writer's appreciation is expressed also to his colleagues for constructive criticism of the paper and to members of the Gravity Section and Geophysical Map Control Unit of the Gulf Research and Development Company who aided in the preparations of the illustrations.

MAGNETIC SUSCEPTIBILITY MEASUREMENTS IN MINNESOTA
PART II: ANALYSIS OF FIELD RESULTS*

HAROLD M. MOONEY† AND RODNEY BLEIFUSS††

ABSTRACT

75 samples of 7 rock types have been analyzed for magnetite content by magnetic separation and chemical analysis, making allowance for iron which occurs as ilmenite, hematite, and silicates. Magnetic susceptibility shows a clear dependence on magnetite content but with too much scatter to permit prediction of one from the other. For small magnetite content V (in volume percent), susceptibility k is roughly given by $k=3{,}000\times10^{-6}\ V$ cgs. Based on 200 outcrops of 11 rock types, the approximate mean susceptibility of basalt and diabase is $2{,}500\times10^{-6}$, of rhyolite and gabbro $1{,}000\times10^{-6}$, of acid intrusives including granite 400×10^{-6}, of greenstone 100×10^{-6}, and of slates 50×10^{-6}. Variability is high for acid intrusives, intermediate for basalt, rhyolite, and greenstone, and lower for diabase, gabbro, and slate.

INTRODUCTION

Part I (reference 6) described a laboratory and an outcrop method for measuring magnetic susceptibility k at field strengths comparable to that of the earth. It was shown that k may change appreciably over distances of a few feet on an apparently homogeneous outcrop, an observation confirmed by the work of Morley (7). The present paper 1) describes a method for measuring magnetite content of rocks, 2) shows the dependence of k on magnetite content, and 3) presents data on susceptibility and its variability for several common rock types.

DETERMINATION OF MAGNETITE CONTENT

Four general methods have been used for determining the magnetite content of rocks: modal analysis, chemical analysis, magnetic separation, and density measurements. Grenet (3) applied modal analysis to thin sections. Bersudskii (1) extended this to polished sections. Nagata (8) and Kato (4) calculated normative magnetite from a complete chemical analysis. Nettleton and Elkins (9) suggest reasons to expect erroneously low values by this method. Werner (13) estimated magnetite content in terms of the relative densities for pure magnetite and the ore sample, a method applicable only to rich ores of simple mineralogy. Puzicha (10) and Slichter (12) applied direct magnetic separation to pulverized samples.

Data reported here were found by magnetic separation, with analysis for iron and titanium. The following steps were used:

1) Pulverize sample to -200 mesh.
2) Pass sample through Davis magnetic separator.
3) Leach the concentrate with 50 percent nitric acid, dry, and weigh.
4) Fuse the product with potassium pyrosulphate, leach, and analyze the

* Manuscript received by the Editor December 20, 1952.
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†† Oliver Iron Mining Company.

filtrate for iron (by titration) and titanium (by colorimetric test).

5) Calculate titanium as ilmenite, subtract ilmenite iron from total iron, and calculate the remainder as magnetite.

The principal uncertainty in magnetite determination by magnetic separation comes from wrongly identifying, as magnetite, some of the iron in the concentrate. Grinding to −200 mesh will ordinarily liberate only a small portion of the magnetite. As a result, the concentrate will contain many locked grains of magnetite with ilmenite, hematite, or iron-bearing silicates, sulphides, or carbonates. The grinding process will introduce metallic iron. All of these must be accounted for before reliable results can be expected. In addition, some of the magnetite might not be retained in the concentrate; analysis of the tailings from the magnetic separator showed losses from this source to be negligible.

The nitric acid leach effectively removes metallic iron, sulphides, and carbonates. The potassium pyrosulphate fusion breaks down the metallic oxides but does not affect the silicates, which can then be rejected. The effectiveness of this separation was confirmed by experiments on samples of augite and by microscopic examination of the residues obtained from the pyrosulphate fusion.

Analysis for titanium accounts for iron present as ilmenite, assuming this to be the only titanium mineral in the magnetic concentrate. This correction proved necessary for basalt, diabase, and gabbro. For these three, the average ilmenite/magnetite ratio (by weight) was 0.16, 0.20, and 0.14; no other rock type gave average values greater than 0.01.

No adequate correction could be made for non-magnetic iron oxides such as hematite. To the extent that grinding to −200 mesh liberates these particles, they will pass into the tailings. Most of the rock types studied here would not be expected to contain appreciable amounts of hematite. Certain reddish-colored rocks such as rhyolite and red rock (diabase differentiate) owe their color to hematite, and the possibility for error will be greatest for these. Schwartz and Sandberg (11) report, however, that hematite occurs as a surface dust on the minerals of these rocks, with small (but unspecified) total content.

SUSCEPTIBILITY *vs.* MAGNETITE CONTENT

There is general agreement that 1) the magnetic behavior of rocks is chiefly due to magnetite, 2) the ferromagnetic components occur as microcrystals of varying composition, with magnetite, ilmenite, and other minerals in solid solution, and 3) susceptibility can be predicted only approximately from magnetite content. Table II and Figures 1–3 offer confirming data for a variety of rock types.

Several writers (for example 8, 10, 13) have shown that disseminated magnetic grains (susceptibility K, volume percent V) in a non-magnetic matrix will show an apparent susceptibility k given by

$$k = \frac{K(V/100)}{1 + PK(1 - V/100)}$$

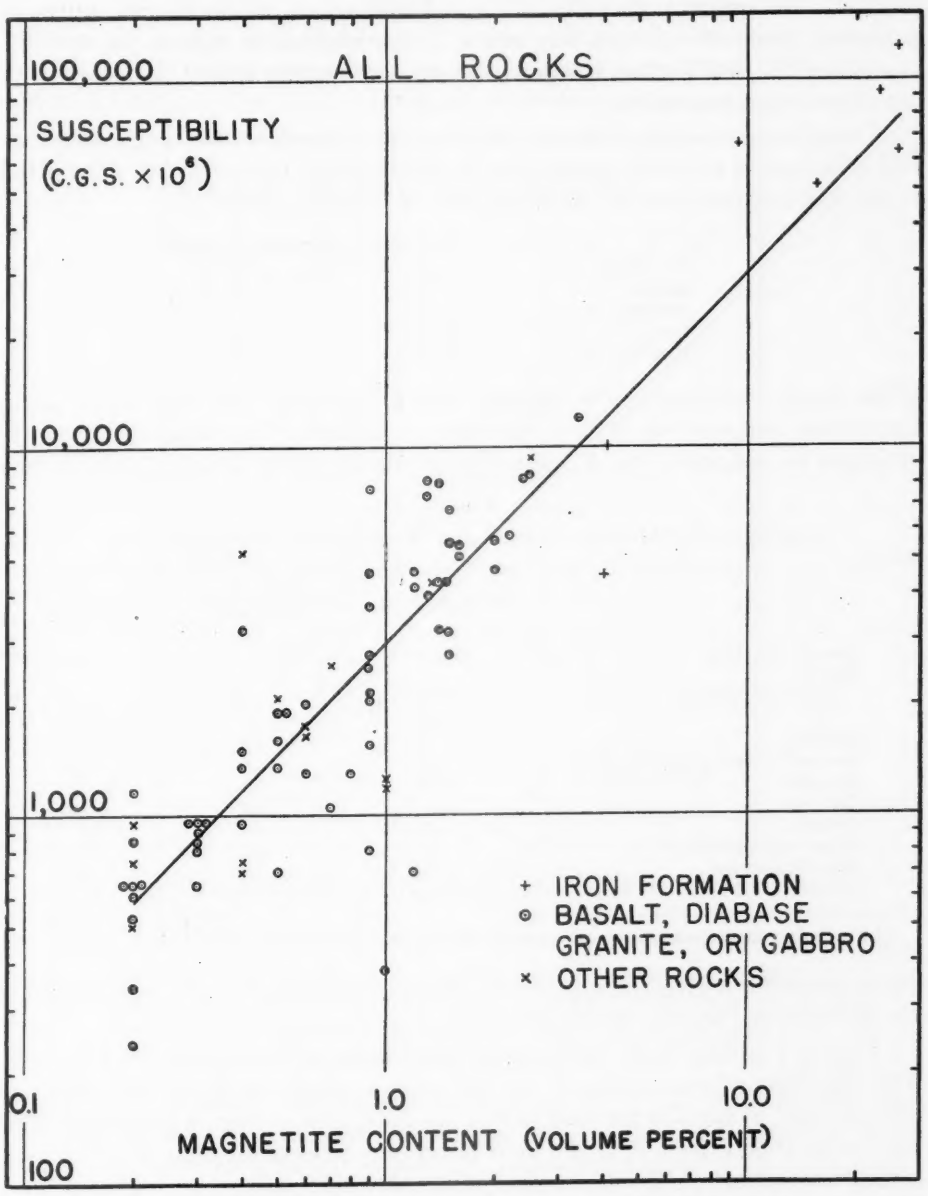

FIG. 1. Experimental data, K_s *vs.* magnetite content for all rocks, with least squares line superposed.

where P is a demagnetization factor dependent on shape and orientation of the particles. For spherical particles, $P=4.2$; Puzicha (10), working with synthetic mixtures, found $P=3.2$–3.9. For small V, the expression reduces to $k=K(V/100)/(1+PK)=k'V$. k now depends largely on P rather than K, as Morley (7) has shown experimentally.

Cartesian plots of the data of Table I show a severe scatter, suggesting that this relationship has little prediction value for rocks. Least squares lines fitted to the k_s laboratory data in the range $0.2\% \leqq V \leqq 3.5\%$ give

	$k' \times 10^6$	*Number of samples*
All rocks	3,220	75
Basalt	3,720	16
Diabase	3,100	16
Granite	2,370	10
Gabbro	1,710	19

While hardly conclusive, this suggests that k' increases with decrease of grain size. Other workers (see 5) have reported the opposite. The data do not justify attempts to compute P or K, especially on the doubtful assumption that they

TABLE I

A SUMMARY OF MAGNETIC SUSCEPTIBILITY DATA TAKEN ON ROCK OUTCROPS

	Mean $k_L \times 10^6$	Coefficient of Variation*	Number of Samples
Iron Formations	56,000	—	7
Basalt			
Non-amygdaloidal	3,660	77%	29
All	2,950	97	37
Diabase	2,590	42	19
Red rock (diabase differentiate)	2,380	99	8
Rhyolite	1,120	89	5
Gabbro	990	54	37
Granite	470	162	31
Other acid intrusives	350	142	17
Ely Greenstone	90	95	15
Slates	50	37	26

* Coefficient of variation = 100 (standard deviation/mean).

are constant for a given rock type. Failure of this assumption probably accounts for the observed scatter, although this cannot be proved.

Figures 1–3 show least squares lines fitted to logarithmic plots, for $V \geqq 0.2\%$. The logarithmic presentation 1) avoids extreme weighting of the end points in curve fitting, 2) spreads the data more uniformly, and 3) offers a prediction basis (of k from V or V from k) which more accurately reflects the high observed variability. Constants for the least squares lines, $k_s = AV^B$, are

	$A \times 10^6$	B
All rocks	2,890	1.01
Basalt	3,780	1.08
Diabase	2,670	1.14
Granite	1,940	0.47
Gabbro	1,230	0.36

These data are not strictly comparable with Cartesian plots, but it is of interest to note that, for all rocks, $k_s = 2{,}890 \times 10^{-6}$ cgs at $V = 1$ percent. Puzicha (10) found $2{,}400$–$2{,}900 \times 10^{-6}$, Slichter (12) $2{,}700$–$2{,}900 \times 10^{-6}$; Grenet (3), Kato (4), and Nagata (8) found, respectively, 1,560, 1,160, and $1{,}150 \times 10^{-6}$. Nettleton and Elkins (9) suggest that the last three err on the low side.

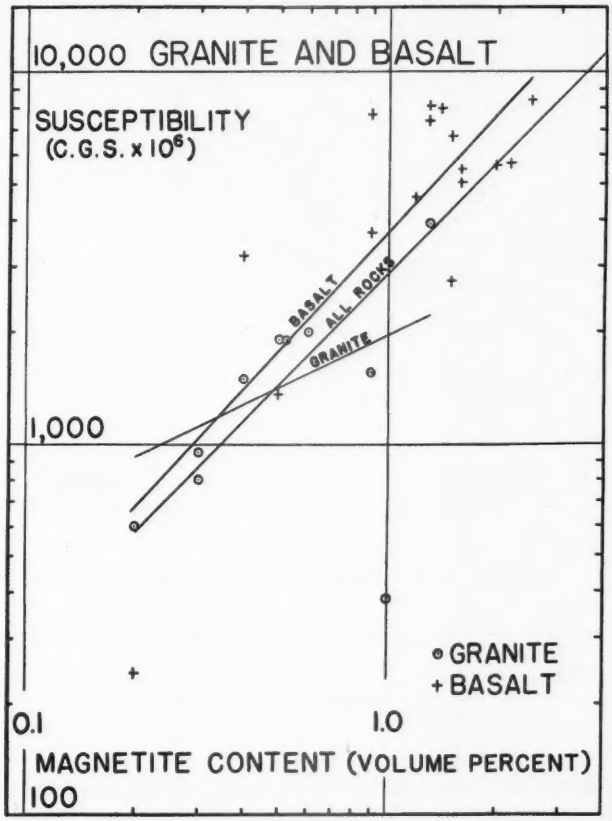

FIG. 2. Experimental data, k_s *vs.* magnetite content for granite and basalt. Least squares lines superposed.

ROCK SUSCEPTIBILITY

Table I summarizes the data on rock susceptibility and its variation. The interpretation of magnetic surveys requires information on both. The mean susceptibility of a rock formation will determine the general level of magnetic intensity and (when expressed as a contrast with surrounding rocks) the change in magnetic intensity to be expected on crossing a contact. Variability will determine the relief on the magnetic contours over a particular rock type; in favorable situations, it may characterize the rock sufficiently to permit identification from magnetic maps.

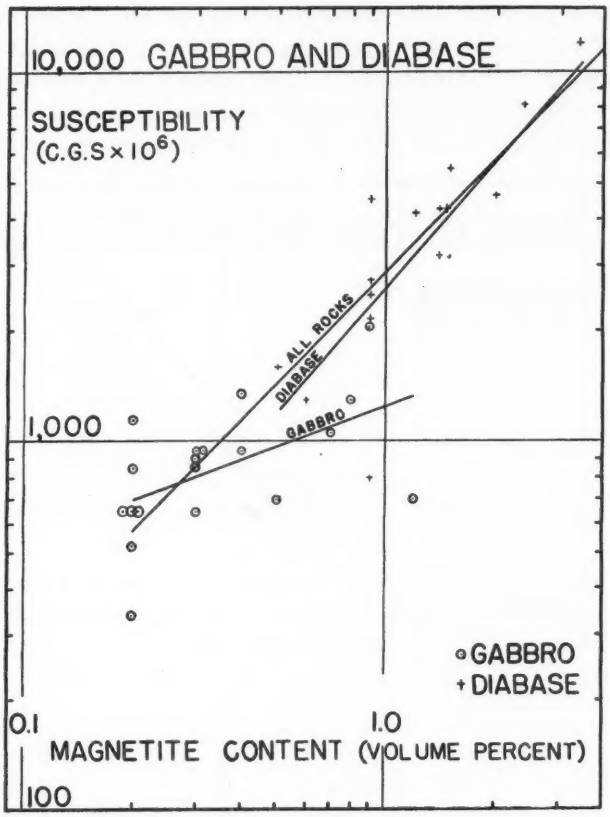

FIG. 3. Experimental data, k_s *vs.* magnetite content for gabbro and diabase. Least squares lines superposed.

Table I suggests the following generalizations, which are generally consistent, where a check is possible, with the results of aeromagnetic surveying in Minnesota. (It should be noted that variability expressed as a percentage implies greater absolute variation at high susceptibility.)

1) Slate and Ely greenstone should appear as areas of low magnetic intensity and low relief.
2) Granite and other acid intrusives may show many magnetic irregularities superposed on a generally low level of intensity.
3) Gabbro should be clearly separable from basic extrusives on the one hand and acid intrusives, greenstones, and slates on the other, through both higher average magnetic level and greater magnetic relief.
4) Basalt might be separable from diabase on the basis of greater magnetic relief (although the occurrence of these rocks in dikes and thin layers would make this difficult).

TABLE II

MAGNETIC AND PETROLOGIC DATA

Rock	Density	k_L	k_s	*Mt*	*Il*
Iron Formation					
Biwabik	3.63	57,000	91,000	23.1	*
Biwabik	3.45	55,000	64,000	25.9	*
Soudan	3.49	115,000	115,000	—	—
Soudan	3.16	98,000	122,000	26.1	*
Soudan	3.07	42,000	52,000	15.4	*
(jasper phase)	2.82	15,000	4,500	4.0	*
(jasper phase)	2.81	10,000	10,000	4.1	*
Basalt					
	2.85	9,600	7,400	1.3	0.4
(porphyritic)	2.86	8,800	8,400	2.5	0.6
(porphyritic)	2.84	8,800	7,700	0.9	0.4
(porphyritic)	2.86	8,450	8,000	1.4	0.6
	2.90	7,600	4,600	1.2	0.3
	3.07	5,900	5,600	2.0	0.1
	3.06	5,500	5,700	2.2	0.2
	2.87	5,250	8,100 (7,542†)	1.3	0.1
	2.92	4,800	5,150	—	—
	2.93	4,800	6,750	1.5	0.3
	2.99	4,600	5,050	1.6	0.2
	2.93	4,350	5,450	1.6	0.4
	2.95	3,700	950	—	—
(prophyritic)	2.74	3,650	3,200	0.4	0.1
	2.98	2,900	1,750	—	—
	3.05	2,900	2,750	1.5	0.1
(amygdaloidal)	2.83	1,950	3,700	0.9	0.1
	3.01	1,900	900	—	—
	2.92	1,850	500	—	—
	2.98	1,800	950	—	—
(porphyritic)	2.75	1,600	240	0.2	*
	3.00	1,600	600	—	—
	2.78	1,600	1,350	—	—
	2.97	1,600	2,850	—	—
	2.90	1,500	1,650	—	—
	2.98	1,350	600	—	—
	3.01	1,300	1,550	—	—
	2.72	1,000	1,350	0.5	*
	2.84	360	360	*	*
(amygdaloidal)	2.64	320	400	0.1	*
	2.92	200	100	0.1	*
(amygdaloidal)	2.87	140	100	0.2	*
	2.94	120	100	—	—
(amygdaloidal)	2.97	120	80 (94†)	—	—
(amygdaloidal)	2.74	100	60	*	*
	2.89	100	40	0.2	*
(amygdaloidal)	2.82	80	60	0.1	*
	2.73	80	80	*	*
(amygdaloidal)	2.75	40	40	*	*
(amygdaloidal)	2.53	0	20	*	*
Diabase					
	2.74	5,200	4,550	0.9	0.2
	2.89	4,600	3,150	1.5	0.1

k_L, k_s: susceptibility in c.g.s.$\times 10^6$, for outcrop (large sample) and laboratory (small sample) measurements. Data rounded off consistent with precision specified in Part I.

Mt, *Il*: magnetite and ilmenite content in volume percent.

* Less than 0.1 percent.

† Independent small sample measurement, by courtesy of Dr. Joseph Sharpe.

TABLE II—*Continued*

Rock	Density	k_L	k_a	*Mt*	*Il*
Diabase					
	2.82	3,750	4,300 (4,724†)	1.4	0.4
	2.85	3,600	4,650	2.0	0.1
	2.88	3,000	5,500	1.5	0.2
	3.10	3,000	3,200	1.4	0.2
	2.79	2,900	2,750	0.9	0.3
	2.92	2,800	8,150	2.4	0.2
	2.86	2,700	4,250	1.4	0.1
	3.03	2,650	4,150	1.2	0.9
	2.86	2,150	12,000	3.4	0.4
	3.04	2,100	2,150	0.9	0.3
(ophitic)	2.98	1,700	2,500	0.9	0.1
	2.83	1,700	800	0.9	0.3
	2.95	1,400	1,300 (1,366†)	—	—
	3.06	1,340	—	—	—
	2.90	1,300	1,300	0.6	02
	3.06	1,300	1,600	0.5	0.1
Red Rock (diabase differentiate)	2.80	7,250	9,450	2.5	0.4
	2.71	5,100	5,200	0.4	*
	2.68	2,550	2,550	0.7	0.1
	2.70	1,150	1,150 (845†)	—	—
	2.74	1,150	1,200	1.0	0.2
	2.74	880	2,100	0.5	0.2
	2.72	700	1,650	0.6	0.1
	2.72	220	100	0.2	*
Rhyolite					
	2.60	3,000	160	0.2	*
	2.61	1,100	700	0.4	*
	2.60	850	750	0.4	*
	2.58	650	500	0.2	*
	2.50	20	20 (20†)	—	—
Gabbro					
	3.13	2,350	2,050	0.9	0.1
	3.13	2,050	2,700	—	—
	2.98	1,900	1,950	—	—
	3.19	1,900	6,050	—	—
	3.02	1,900	1,700	—	—
	3.01	1,550	2,500	—	—
	2.88	1,400	1,550	—	—
	2.81	1,300	1,500	—	—
	2.98	1,250	1,350	0.4	0.1
	3.05	1,250	1,300 (3,697†)	0.8	0.2
	2.80	1,300	1,150	0.2	0.1
	2.82	1,200	850	0.2	*
	2.83	1,150	1,300	—	—
	2.87	1,100	650	0.2	*
	2.99	1,000	1,250	—	—
	2.90	950	900	0.3	0.1
	2.94	900	850	0.3	0.1
	2.77	900	140	—	—
	2.79	850	1,200	—	—
	2.79	850	260	—	—
	2.73	850	700	0.5	0.1
	2.92	800	950 (1,073†)	0.3	0.1
	2.88	800	700 (844†)	1.2	*
	2.96	750	950	0.3	0.1
	2.89	650	650	0.3	0.1
	2.80	600	80	0.1	*
	2.98	600	650	0.2	0.1

TABLE II—*Continued*

Rock	Density	k_L	k_a	*Mt*	*Il*
	2.99	560	950	0.4	0.1
	2.91	520	1,050	0.7	0.1
	2.90	520	650	0.2	*
	2.79	480	400	*	*
	2.76	440	80	0.1	*
	2.97	360	340	0.2	*
	2.98	200	220	0.2	*
	2.95	120	80	0.3	*
	2.82	120	520	0.2	*
Granite					
(Giants Range)	2.71	2,950	1,550 (1,758†)	0.9	*
	2.65	750	200	—	—
	2.70	650	800 (796†)	0.3	*
	2.65	600	600	0.2	*
	2.71	600	950	0.3	*
	2.65	400	380	1.0	*
	2.77	320	2,000	0.6	0.1
	2.64	220	20	0.2	*
	2.66	60	0	—	—
	2.60	40	0	0.2	*
	2.66	20	0	0.1	*
	2.63	20	20	0.2	*
	2.66	20	20	—	—
	2.69	20	20	0.1	*
	2.62	20	0	—	—
	2.63	20	20	0.1	*
(Central Minnesota Red)	2.74	2,700	3,950	1.3	*
	2.66	140	140	—	—
	2.66	120	140 (152†)	0.2	*
	2.66	120	20	0.1	*
	2.63	80	60	0.1	*
	2.66	20	20	0.1	*
	2.63	20	20	0.1	*
	2.64	20	20	0.1	*
(Central Minnesota Gray)	2.74	1,600	1,900	0.5	*
	2.72	1,550	1,500	0.4	*
	2.75	1,500	1,900	0.5	*
	2.88	40	60	*	*
	2.75	40	40	0.1	*
	2.73	20	40	0.1	*
	2.71	20	40	0.1	*
Minor Intrusives					
(Granodiorite)	2.92	900	950	0.2	*
	2.92	550	750	0.2	*
	2.80	60	20	*	*
(McGrath Gneiss)	2.64	1,800	180	0.2	*
	2.66	1,200	1,700	0.6	*
	2.73	650	4,300	1.4	*
	2.64	400	1,250 (1,548†)	1.0	*
	2.69	200	20	*	*
	2.68	60	40	0.2	*
	2.68	20	20	0.1	*
(Hilldale tonalite)	2.89	40	40	*	*
	2.85	40	60	0.1	*
	2.71	20	20	*	*
	2.72	20	40	0.1	*
(Quartz monzonite)	2.83	20	40	0.1	*
	2.70	20	0	0.1	*
	2.71	20	0	0.1	*
(Anorthosite)	2.71	40	80 (83†)	—	—

TABLE II—*Continued*

Rock	Density	k_L	k_s	*Mt*	*Il*
Ely Greenstone					
	3.03	380	900	0.2	*
	2.89	100	60	0.1	*
	3.00	100	100	0.2	*
	3.07	100	80 (92†)	0.2	*
	3.04	80	60 (111†)	0.2	*
	3.01	60	40	—	—
	3.03	60	80	0.2	*
	2.95	60	60	—	—
	2.85	60	60	—	—
	2.88	60	40	0.2	*
	2.86	40	40	0.2	*
	2.87	40	40	0.1	*
	2.89	40	40	0.2	*
	2.92	40	40	0.1	*
Slates					
(Knife Lake)	2.72	60	20	—	—
	3.03	80	60 (90†)	0.1	—
	2.74	80	100	0.1	—
	2.77	80	20	0.1	—
	2.72	60	20	—	—
	2.70	40	0	*	—
	2.77	100	60	0.2	—
	2.73	40	20 (59†)	0.1	—
(Rove)	2.72	80	20	*	—
	2.72	60	20 (59†)	0.1	—
	2.65	40	60	0.1	—
(Virginia)	2.69	80	40	*	—
(Thompson)	2.65	80	20	*	
	2.80	60	20	*	
	2.92	60	20	*	
	2.82	40	40	*	
	2.76	40	40	*	
	2.80	40	40	*	
	2.91	40	0	*	
	2.74	40	40	*	
	2.85	40	40	0.1	
	2.78	40	40	*	
	2.87	40	40	0.1	
	2.80	40	40	*	
	2.93	40	40	0.1	
	2.73	20	20	*	
	2.74	20	20	*	

5) Rhyolite should show a distinctly lower magnetic level than basalt.

The data do not support a suggestion of Bruckshaw and Rao (2), that extrusives such as basalt might show abnormally high variability as a result of rapid cooling and subsequent reheating.

CONCLUSIONS

1) The magnetite content of rocks can be found by magnetic separation and chemical analysis, provided precautions are taken to assure liberation of the magnetite and to account for iron present as ilmenite, hematite, and silicates.

2) Magnetic susceptibility k shows a clear dependence on magnetite content

V, but the data scatter too much to permit reliable prediction of one from the other. k increases more rapidly with V for fine-grained extrusives than for coarse-grained intrusives.

3) Mean susceptibilities of the rock types studied differ significantly, but individual values overlap.

4) The mean susceptibilities of acid intrusives, basic intrusives, and basic extrusives are in the ratio 1:2:7; relative variabilities in the ratio 3:1:2.

ACKNOWLEDGMENTS

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A LEAST SQUARE METHOD FOR GRAVITY METER BASE STATIONS*

H. H. PENTZ

ABSTRACT

Two applications of the Method of Least Squares in determining the most probable values from gravity meter base station applications are considered. One is an approximation, the degree of approximation depending on the number of base stations. The second is a rigorous application of the Method of Least Squares in obtaining the most probable values for an expanding base station network.

The practical application of the Method of Least Squares to gravimeter surveys is made difficult by the fact that most surveys cover large areas with the base stations being established as the survey continues. Under these conditions it is necessary to have some method of adjustment based on the Method of Least Squares.

Referring to Figure 1, let it be required to determine C from two old base stations A and B. The conditional equations for the network reduce to

$$\begin{aligned} v_1 + v_2 &= d_a \\ v_1 + v_3 + v_5 &= d_1 \\ v_2 + v_4 + v_6 &= d_2 \\ v_5 + v_7 + v_9 &= d_3 \\ v_6 + v_8 + v_{10} &= d_4 \\ &\cdots\cdots\cdots, \end{aligned}$$

where $v_1, v_2, v_3, \cdots$ are small corrections applied to BC, AC, $\cdots$, and d_a, d_1, $d_2, \cdots$ are small quantities called discrepancies which are numerically equal to but opposite in sign to the closure error. The weights of all observations are assumed equal.

The method of correlates deduces normal equations, equal in number to the number of conditional equations, which are:

$$\begin{aligned} [a^2]k_1 + [ab]k_2 + [ac]k_3 + \cdots &= d_a \\ [ab]k_1 + [b^2]k_2 + [bc]k_3 + \cdots &= d_1 \\ [ac]k_1 + [bc]k_2 + [c^2]k_3 + \cdots &= d_2 \\ &\cdots\cdots\cdots\cdots\cdots, \end{aligned}$$

where $k_1, k_2, k_3, \cdots$ are determined by the solution of the normal equations and

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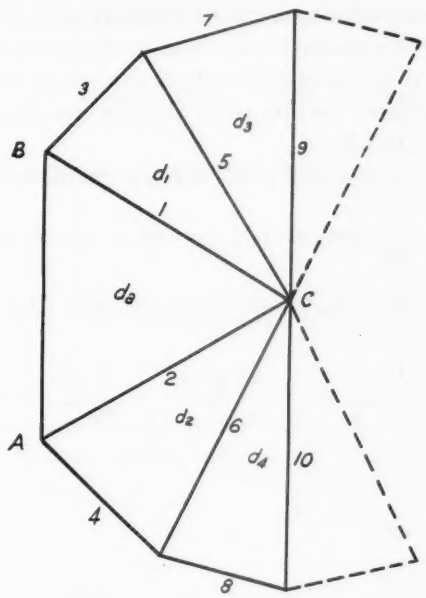

FIG. 1. Base station network for determining one new base C from two old bases A and B.

the brackets indicate summation, namely,

$$[a^2] = a_1^2 + a_2^2 + \cdots, \qquad [ab] = a_1b_1 + a_2b_2 + \cdots,$$

and $a_1, a_2, \cdots$ are the coefficients of the first conditional equation; $b_1, b_2, \cdots$ are the coefficients of the second conditional equation, etc.

By the solution of these normal equations the values of $k_1, k_2, k_3, \cdots$ are found, then the corrections are

$$v_1 = a_1k_1 + b_1k_2 + c_1k_3 + \cdots$$
$$v_2 = a_2k_1 + b_2k_2 + c_2k_3 + \cdots$$
$$\cdots\cdots\cdots\cdots\cdots$$

The normal equations for this particular example are

$$\begin{aligned}
2k_1 + k_2 + k_3 + 0 + 0 + \cdots &= d_a \\
k_1 + 3k_2 + 0 + k_4 + 0 + \cdots &= d_1 \\
k_1 + 0 + 3k_3 + 0 + k_5 + 0 + \cdots &= d_2 \\
0 + k_2 + 0 + 3k_4 + 0 + k_6 + 0 + \cdots &= d_3 \\
0 + 0 + k_3 + 0 + 3k_5 + 0 + k_7 + \cdots &= d_4 \\
\cdots\cdots\cdots\cdots\cdots

This system of normal equations can be built up to an infinite number; but in solving a finite number of equations only as many k's are carried as there are normal equations. Notice that this application is not restricted to the figure given. For example, if the notation for the sides 3 and 5 are interchanged an entirely different network is produced.

The solution for the correction to BC for five conditional equations is

$$v_1 = \frac{1}{80}(40d_a + 15d_1 - 15d_2 - 5d_3 + 5d_4).$$

Now assume that with ABC remaining unchanged other similar networks are observed as in Figure 2. Then

$$v_1 = \frac{1}{80}\left(40d_a + \frac{15}{n}\sum_1^n d_{1n} - \frac{15}{n}\sum_1^n d_{2n} - \frac{5}{n}\sum_1^n d_{3n} + \frac{5}{n}\sum_1^n d_{4n}\right).$$

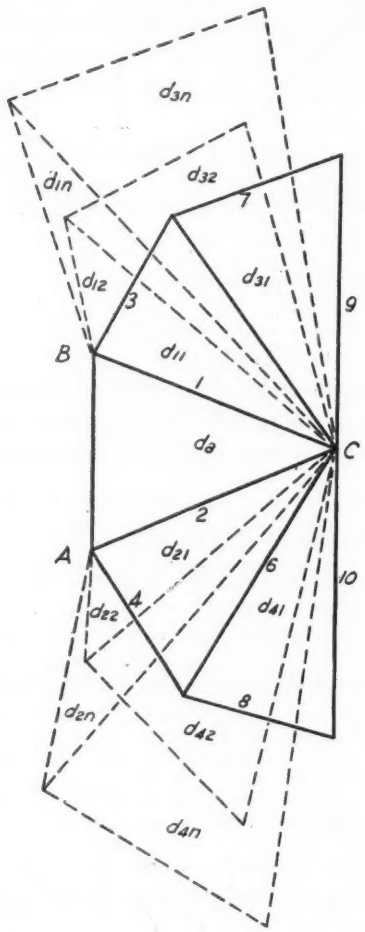

FIG. 2. A particular extension of the base station network of Figure 1.

If n is allowed to increase then

$$\lim_{n\to\infty} v_1 = \frac{1}{80}(40d_a + 15v_1 - 15v_2),$$

and since the network is symmetrical about ABC

$$\lim_{n\to\infty} v_2 = \frac{1}{80}(40d_a + 15v_2 - 15v_1).$$

Solving these two simultaneous equations the correction

$$v_1 = \tfrac{1}{2}d_a.$$

Now consider the base station network in Figure 3. A and B are two established bases and C is a base to be determined. Application of the preceding method of correlates gives

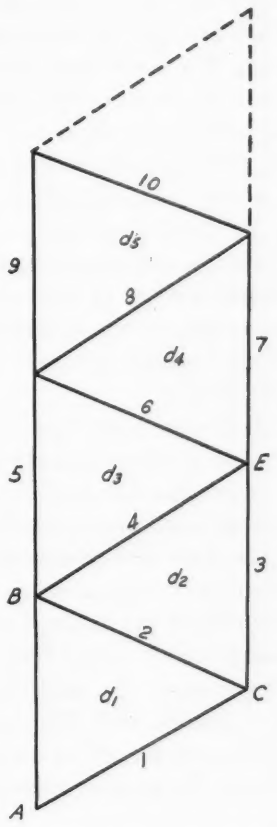

FIG. 3. A triangular base station network of infinite length.

$$v_1 = k_1 = \frac{N_n}{D_n} = \frac{\begin{vmatrix} d_1 & 1 & 0 \cdots 0 & 0 \\ d_2 & 3 & 1 \cdots 0 & 0 \\ d_3 & 1 & 3 \cdots 0 & 0 \\ \cdot & \cdot & \cdot\ \cdot\ \cdot\ \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot\ \cdot\ \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot\ \cdot\ \cdot & \cdot \\ d_{n-1} & 0 & 0 \cdots 3 & 1 \\ d_n & 0 & 0 \cdots 1 & 3 \end{vmatrix}}{\begin{vmatrix} 2 & 1 & 0 \cdots 0 & 0 \\ 1 & 3 & 1 \cdots 0 & 0 \\ 0 & 1 & 3 \cdots 0 & 0 \\ \cdot & \cdot & \cdot\ \cdot\ \cdot\ \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot\ \cdot\ \cdot & \cdot \\ \cdot & \cdot & \cdot\ \cdot\ \cdot\ \cdot & \cdot \\ 0 & 0 & 0 \cdots 3 & 1 \\ 0 & 0 & 0 \cdots 1 & 3 \end{vmatrix}} = \frac{3N_{n-1} - N_{n-2} + (-1)^{n-1}d_n}{3D_{n-1} - D_{n-2}}$$

where $n \geqq 4$. When N_n/D_n is written out for successive values of n it is apparent that this value approaches a limit. This is more readily demonstrated by the conditional equation $v_1+v_2=d_1$. The correction v_1 must be less than d_1 unless d_1 equals zero. After some value of n is reached the addition of further terms in the solution for v_1 is less than the observation error and they may be ignored.

The correction $v_2=d_1-v_1$. The second conditional equation may be written $v_3+v_4=d_2-v_2$. The base C has now been determined and, adding another closure to the network to maintain the required accuracy, the process may be repeated in determining the base E from the two known bases B and C. This application can be extended to the determination of additional intermediate bases, for example along BC, but the weight of the observation BC, depending on the number of bases along BC that are used to observe BC, would then have to be considered in the above application.

Two applications of the Method of Least Squares to the problem of obtaining the most probable values of gravity meter base stations are considered. The first may be considered as an approximation which becomes closer to the most probable value as the number of conditional equations increases. The field practice of taking the average value of the new base as determined from two old bases is thereby shown not to depart too far from the most probable values as determined by the rigorous application of the Method of Least Squares. The second application will give the most probable values for a finite but unknown number of base stations as long as the number of conditional equations required to produce the necessary accuracy is maintained. This base station network could be terminated at any time but if it was desired to use all the base stations it would then become necessary to solve the normal equations for all values of the k's and the v's from them.

REFERENCE

Mansfield Merriman: *Elements of Precise Surveying and Geodesy*, John Wiley & Sons, New York, 1904.

APPENDIX

Solution of the determinate for N_n

$$N_n = \begin{vmatrix} d_1 & 1 & 0 & 0 \cdots 0 & 0 \\ d_2 & 3 & 1 & 0 \cdots 0 & 0 \\ d_3 & 1 & 3 & 1 \cdots 0 & 0 \\ d_4 & 0 & 1 & 3 \cdots 0 & 0 \\ \cdot & \cdot & \cdot & \cdot \cdots \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \cdots \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \cdots \cdot & \cdot \\ d_{n-1} & 0 & 0 & 0 \cdots 3 & 1 \\ d_n & 0 & 0 & 0 \cdots 1 & 3 \end{vmatrix}$$

$$N_2 = \begin{vmatrix} d_1 & 1 \\ d_2 & 3 \end{vmatrix} = 3d_1 - d_2$$

$$N_3 = \begin{vmatrix} d_1 & 1 & 0 \\ d_2 & 3 & 1 \\ d_3 & 1 & 3 \end{vmatrix} = 3N_2 - \begin{vmatrix} d_1 & 1 \\ d_3 & 1 \end{vmatrix} = 3N_2 - d_1 + d_3$$

$$N_4 = \begin{vmatrix} d_1 & 1 & 0 & 0 \\ d_2 & 3 & 1 & 0 \\ d_3 & 1 & 3 & 1 \\ d_4 & 0 & 1 & 3 \end{vmatrix} = 3N_3 - \begin{vmatrix} d_1 & 1 & 0 \\ d_2 & 3 & 1 \\ d_4 & 0 & 1 \end{vmatrix} = 3N_3 - N_2 - d_4$$

$$N_5 = \begin{vmatrix} d_1 & 1 & 0 & 0 & 0 \\ d_2 & 3 & 1 & 0 & 0 \\ d_3 & 1 & 3 & 1 & 0 \\ d_4 & 0 & 1 & 3 & 1 \\ d_5 & 0 & 0 & 1 & 3 \end{vmatrix} = 3N_4 - \begin{vmatrix} d_1 & 1 & 0 & 0 \\ d_2 & 3 & 1 & 0 \\ d_3 & 1 & 3 & 1 \\ d_5 & 0 & 0 & 1 \end{vmatrix}$$

$$= 3N_4 - N_3 + d_5$$

$$N_6 = \begin{vmatrix} d_1 & 1 & 0 & 0 & 0 & 0 \\ d_2 & 3 & 1 & 0 & 0 & 0 \\ d_3 & 1 & 3 & 1 & 0 & 0 \\ d_4 & 0 & 1 & 3 & 1 & 0 \\ d_5 & 0 & 0 & 1 & 3 & 1 \\ d_6 & 0 & 0 & 0 & 1 & 3 \end{vmatrix} = 3N_5 - \begin{vmatrix} d_1 & 1 & 0 & 0 & 0 \\ d_2 & 3 & 1 & 0 & 0 \\ d_3 & 1 & 3 & 1 & 0 \\ d_4 & 0 & 1 & 3 & 1 \\ d_6 & 0 & 0 & 0 & 1 \end{vmatrix}$$

$$= 3N_5 - N_4 + \begin{vmatrix} d_1 & 1 & 0 & 0 \\ d_2 & 3 & 1 & 0 \\ d_3 & 1 & 3 & 1 \\ d_6 & 0 & 0 & 0 \end{vmatrix} = 3N_5 - N_4 - \begin{vmatrix} d_1 & 1 & 0 \\ d_2 & 3 & 1 \\ d_6 & 0 & 0 \end{vmatrix}$$

$$= 3N_5 - N_4 - d_6 \begin{vmatrix} 1 & 0 \\ 3 & 1 \end{vmatrix} = 3N_5 - N_4 - d_6$$

$$N_n = 3N_{n-1} - N_{n-2} + (-1)^{n-1} d_n$$

where $n \geqq 4$.

APPROXIMATION TO THE LATERAL VARIATION OF RESIDUAL GRAVITY DUE TO A FRUSTUM OF A VERTICAL CONE*

W. RAYMOND GRIFFIN†

ABSTRACT

The equation for the subject title is presented in nondimensional form. The approximation consists of considering a frustum of a vertical cone in which the radii are small relative to the depth to its top.

The dependent variable has been taken as being the ratio of the residual gravity (as defined in a previous publication by the author) to the maximum residual gravity.

The independent variable was chosen as the ratio of the lateral distance (from the center line of the frustum to a given station) to the depth to the top of the frustum.

The two parameters were chosen as being

(a) The ratio of depth to the bottom of the frustum to that to its top,

(b) The ratio of the bottom radius to that of the top radius.

It is then shown that, for special values of the parameters, the equation gives the lateral variation of residual gravity due to cylinders, upright cones, and inverted cones as special cases.

Tables of the principal functions, which occur in the equation, are given over practical ranges of values. Graphs of the equation are given. They cover the practical range for each of the variables and each of the parameters.

Application of the equation is made to two Gulf Coast salt domes whose dimensions are rather well known from previous drilling. Graphs, showing the degree of correlation, are given.

The conclusion is drawn that, despite the approximation involved in the derivation of the equation, and despite the departure of the ratio of the dimensions of the salt domes from that assumed, the correlation with the actual gravity values for two deep salt domes is remarkably close.

INTRODUCTION

This paper is an outgrowth of a study initiated to investigate the sensitivity of the lateral variation of residual gravity to departures of structural shape of the causative mass from that of a vertical cylinder to that of a frustum of a vertical cone. Common practice in the past for analysis of salt domes has been to assume that they are vertical cylinders. It is highly probable, however, that the actual shape is more frequently that of a frustum.

As an example of such domes one might cite the West Columbia salt dome as described by Carlton (1929). Another example is that of the South Houston salt dome. This may be seen by an examination of Figure 1 of Eby's (1945) article on that dome. He states that it is one of the steepest on the Gulf Coast. Therefore, the majority of salt domes evidently depart even more from that of a vertical cylinder.

The writer is only too keenly aware of the non-uniqueness of quantitative gravity analyses (Skeels, 1947). However, in a *known* geologic province, such as that of the Gulf Coast, such analyses are not without their value and use.

It is to be understood, of course, that the present study is applicable not only to salt domes but also to any frustum-like structure. For example, it should be

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of possible use in the analyses of buried volcanoes, or even of certain reefs.

Due to the mathematical complexities encountered in the process of solving the problem posed here the solution was carried out only for the limiting case of the frustum's top radius being small relative to the depth to its top. Fortunately, however, this is just the case of greatest interest at this time. Practically all of the shallow domes have already been found, at least on land. Deep domes are about the only ones left, and these are the ones to which the present study is particularly applicable.

THE GENERAL FORMULA

Referring to Figure 1 and its nomenclature, and by use of Newton's Law of Universal Gravitation, the formula for the lateral variation of gravity is derived as being

$$g_Z = \pi\gamma\sigma \int_{Z_T}^{Z_B} \frac{R^2 Z dZ}{(r^2 + Z^2)^{3/2}} \tag{1}$$

where

g_Z = vertical component of gravitational attraction at "G" due to the frustum (Fig. 1)

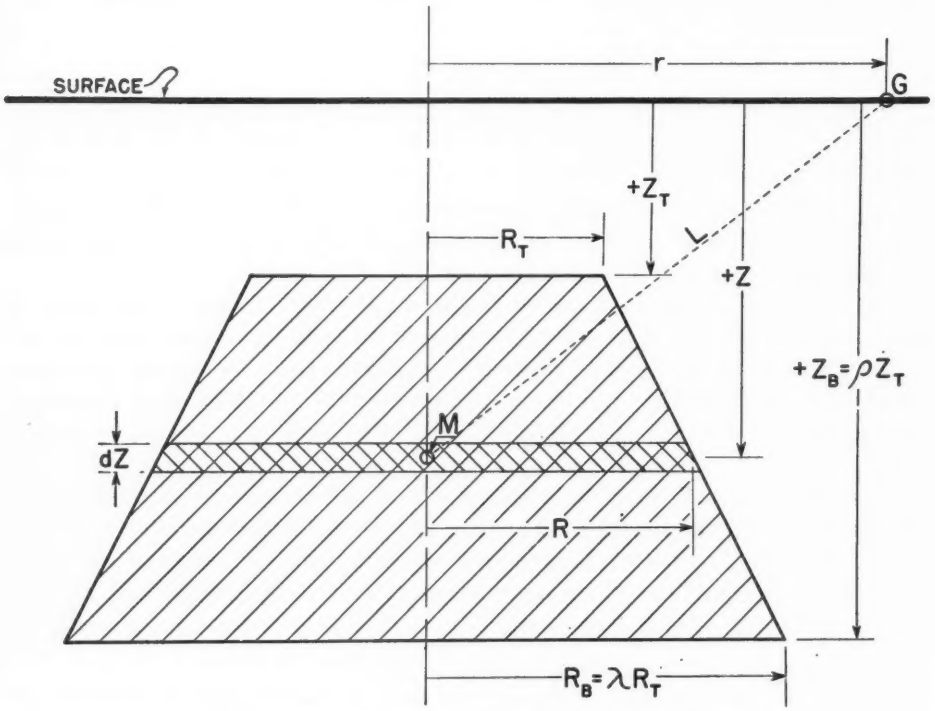

FIG. 1. Dimensions associated with a vertical frustum.

γ = gravitational constant
Z = depth to point "M" (Fig. 1).
R = radius of frustum at depth "Z."
r = radial distance from center line of frustum to point "G."

The subscripts "T" and "B" refer, respectively, to the top and bottom of the given frustum.

Now, the variable frustum radius, "R," is given by

$$R = R_T + s(Z - Z_T), \tag{2}$$

where s = slope of frustum. The slope, in turn, is given by

$$s = (R_B - R_T)/(Z_B - Z_T). \tag{3}$$

This may also be written as

$$s = \mu\beta \tag{4}$$

where

$$\mu = R_T/Z_T$$
$$\beta = (\lambda - 1)/(\rho - 1)$$
$$\lambda = R_B/R_T$$
$$\rho = Z_B/Z_T.$$

Placing (2) and (4) in (1), integrating, putting in limits, and placing in non-demensional form the independent variable, "r," and the dependent variable "g_z," the general formula is arrived at as being

$$\Gamma = \frac{(1 - 2\beta)A(\rho, u) - 2\beta B(\rho, u) - \beta^2 C(\rho, u)}{(1 - 2\beta)A(\rho, \infty) - 2\beta B(\rho, \infty) - \beta^2 C(\rho, \infty)} \tag{5}$$

where $u = r/Z_T$ is the independent variable and

$$\Gamma = (\Delta g)/(\Delta g)_{\max},$$

as derived in a previous publication by the writer, is the *dependent* variable.

The three functions of "ρ" and "u," $A(\rho, u)$, $B(\rho, u)$, and $C(\rho, u)$ are defined as follows:

$$u = \tan \phi$$
$$u/\rho = \tan \phi'$$
$$\text{cyl } (\rho, u) = \cos \phi - (1/\rho) \cos \phi'$$
$$Q(\rho, u) = (1 + \sec \phi')/(1 + \sec \phi)$$
$$A(\rho, u) = \text{cyl } (\rho, 0) - \text{cyl } (\rho, u)$$
$$A(\rho, \infty) = \text{cyl } (\rho, 0) = 1 - (1/\rho)$$
$$B(\rho, u) = \ln Q(\rho, u) + \cos \phi - \cos \phi'$$

$$B(\rho, \infty) = -\ln \rho$$

$$C(\rho, u) = \rho \operatorname{cyl}^2(\rho, 0)(1 - \cos \phi') - 2\{\rho \operatorname{cyl}(\rho, 0) + \sec \phi - \rho \sec \phi' + \ln Q(\rho, u)\}$$

$$C(\rho, \infty) = \rho \operatorname{cyl}^2(\rho, 0) - 2\{\rho \operatorname{cyl}(\rho, 0) - \ln \rho\}.$$

Here "ln" refers to the natural logarithm.

It will be instructive at this point to consider several special cases of the General Formula (5):

Case I (Cylinder: $\lambda = 1$)

It is evident from Figure 1 that $\lambda = 1$ is the condition for a vertical cylinder. This corresponds to $\beta = 0$, and (5) becomes merely

$$\Gamma = \frac{A(\rho, u)}{A(\rho, \infty)}. \tag{6}$$

For an infinitely long vertical cylinder (i.e., $\rho = \infty$), Equation (6) further reduces to

$$\Gamma = 1 - \cos \phi = 1 - (1 + u^2)^{-1/2}. \tag{7}$$

This is a well known result.

Case II (Upright Cone: $\lambda = \infty$)

It will be observed that, from the definition, $\beta \to \infty$ as $\lambda \to \infty$ and that the terms of (5) involving β become negligible compared to those containing β^2, and thus:

$$\lim_{\beta \to \infty} \Gamma = \frac{C(\rho, u)}{C(\rho, \infty)} \tag{8}$$

gives the lateral variation of residual gravity due to an upright cone.

(Note: $\lambda \to \infty$ by $R_T \to 0$, and not by $R_B \to \infty$.)

Case III (Inverted Cone: $\lambda = 0$).

For $\lambda = 0$, we have $\beta = -(\rho - 1)^{-1}$. Placing this value of β in (5), multiplying numerator and denominator through by $(\rho - 1)^2$, and simplifying,

$$\Gamma = \frac{(\rho^2 -)A(\rho, u) + 2(\rho - 1)B(\rho, u) - C(\rho, u)}{(\rho^2 - 1)A(\rho, \infty) + 2(\rho - 1)B(\rho, \infty) - C(\rho, \infty)}. \tag{9}$$

Case IV (Frusta Given by $\lambda = \rho$, i.e., $\beta = 1$).

For this particular family of frusta, (5) reduces to

$$\Gamma = \frac{A(\rho, u) + 2B(\rho, u) + C(\rho, u)}{A(\rho, \infty) + 2B(\rho, \infty) + C(\rho, \infty)}. \tag{10}$$

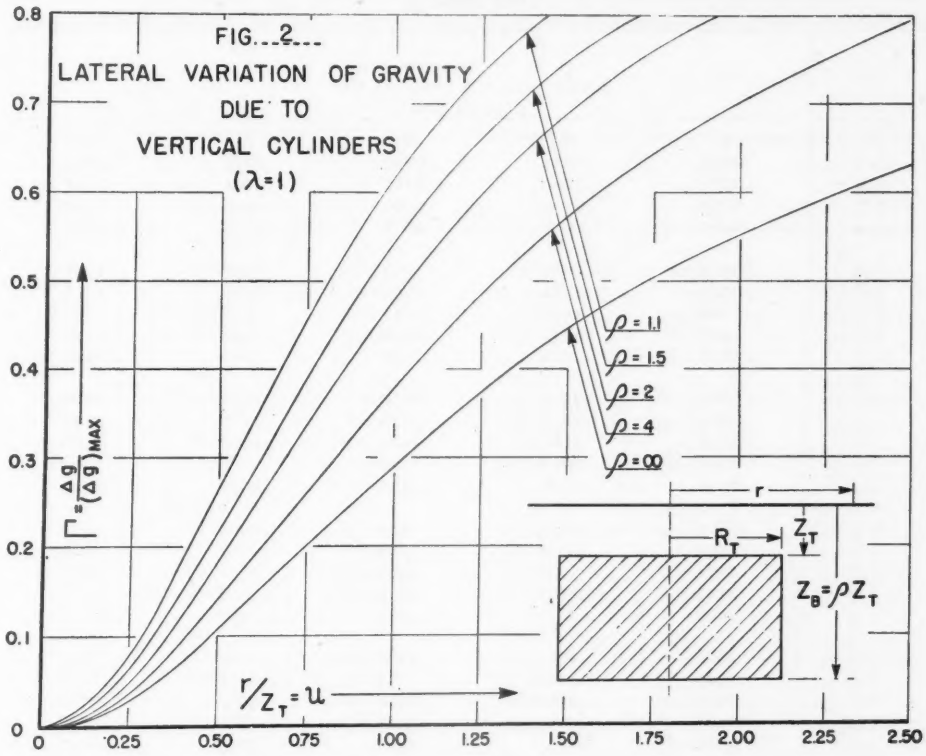

FIG. 2. Lateral variation of residual gravity due to vertical cylinders ($\lambda=1$) vs u.

It is thus seen that (5) is a rather general formula from which Γ for cylinders, upright cones, inverted cones, and certain frusta come out as very simple cases.

TABLES

Tabulated values of $A(\rho, u)$, $B(\rho, u)$, and $C(\rho, u)$ are given in Tables 1, 2, and 3, for various values of ρ and for values of u from $u=0$ by tenths to $u=2.5$, inclusive.

FIGURES

Figure 2 and Figure 3 comprise the graphs of Γ *vs* u and Γ *vs* $(1/u)$ for vertical *cylinders* for various values of ρ. Figures 4, 5, and 6 show Γ *vs* u for various values of ρ respectively and for various values of λ between $\lambda=1$ and $\lambda=\infty$, inclusive. Figures 7, 8, and 9, are also respectively for $\rho=2$, 3, and 4 but with curves for $\lambda=0$ (inverted cone), $\lambda=1$ (cylinder), and $\lambda=\infty$ (upright cone).

EXAMPLES OF APPLICATION OF EQUATION (5)

Example one. Mykawa Field, Harris County, Texas (Fig. 10)

Picking off the center of the Mykawa anomaly from already existing residual gravity maps, an experimental profile of residual gravity *vs* radius of residual

TABLE 1

$+A(\rho, u)$ VS. u
AND FOR $\rho = 1.5, 2, 3, 4,$ AND 6
(Ref. Equa. 5)

u \ ρ	1.5	2	3	4	6
1	0	0	0	0	0
0.1	.0034	.0044	.0049	.0049	.0050
0.2	.0136	.0169	.0187	.0191	.0193
0.3	.0292	.0366	.0406	.0415	.0420
0.4	.0489	.0618	.0686	.0703	.0711
0.5	.0714	.0906	.1011	.1037	.1050
0.6	.0948	.1214	.1361	.1397	.1416
0.7	.1184	.1527	.1721	.1770	.1796
0.8	.1407	.1833	.2079	.2142	.2176
0.9	.1617	.2126	.2427	.2506	.2548
1.0	.1809	.2401	.2759	.2854	.2906
1.1	.1981	.2654	.3070	.3183	.3246
1.2	.2138	.2886	.3361	.3493	.3566
1.3	.2274	.3095	.3629	.3781	.3865
1.4	.2395	.3284	.3876	.4047	.4144
1.5	.2500	.3453	.4101	.4294	.4403
1.6	.2592	.3604	.4309	.4521	.4643
1.7	.2674	.3740	.4497	.4731	.4867
1.8	.2745	.3860	.4669	.4924	.5073
1.9	.2806	.3967	.4825	.5100	.5264
2.0	.2862	.4063	.4986	.5264	.5442
2.1	.2909	.4149	.5099	.5415	.5607
2.2	.2950	.4225	.5218	.5552	.5760
2.3	.2988	.4293	.5325	.5680	.5902
2.4	.3020	.4355	.5424	.5773	.6035
2.5	.3050	.4410	.5514	.5905	.6157
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
∞	.3333	.5000	.6667	.7500	.8333

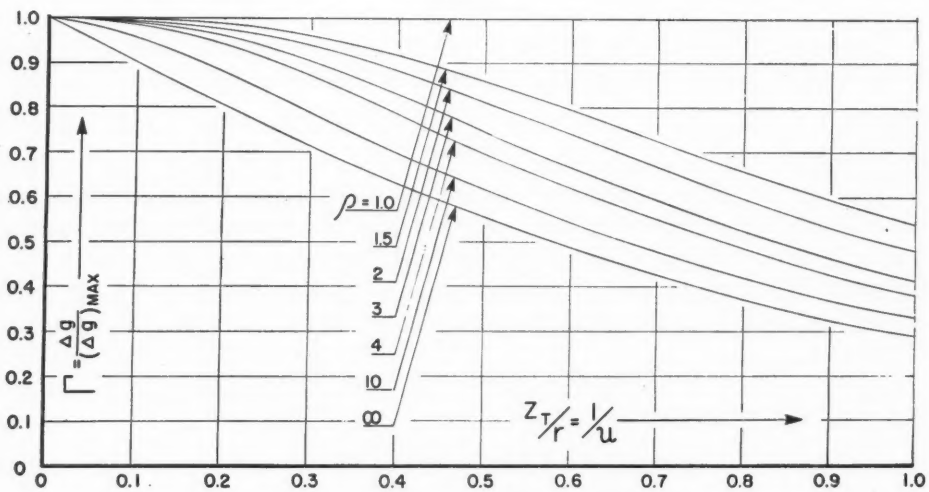

FIG. 3. Lateral variation of residual gravity due to vertical cylinders ($\lambda = 1$) vs ($1/u$). Note: this figure was prepared to show how $\Gamma \to 1.0$ as $u \to \infty$; i.e., as $(1/u) \to 0$

TABLE 2

$-B(\rho, u)$ VS. u
AND FOR $\rho = 1.5$, 2, 3, 4, AND 6
(Ref. Equa. 5)

u \ ρ	1.5	2	3	4	6
0	0	0	0	0	0
0.1	.0040	.0055	.0067	.0070	.0073
0.2	.0162	.0217	.0258	.0273	.0285
0.3	.0347	.0473	.0565	.0598	.0622
0.4	.0581	.0800	.0961	.0918	.0160
0.5	.0852	.1159	.1423	.1514	.1579
0.6	.1131	.1585	.1931	.2057	.2149
0.7	.1416	.2000	.2460	.2629	.2753
0.8	.1685	.2411	.2993	.3212	.3372
0.9	.1937	.2808	.3520	.3792	.3994
1.0	.2168	.3181	.4033	.4359	.4606
1.1	.2380	.3530	.4517	.4908	.5205
1.2	.2572	.3852	.4982	.5436	.5784
1.3	.2738	.4144	.5417	.5963	.6337
1.4	.2888	.4410	.5825	.6410	.6871
1.5	.3017	.4649	.6199	.6857	.7376
1.6	.3128	.4866	.6551	.7277	.7859
1.7	.3232	.5060	.6869	.7671	.8320
1.8	.3320	.5325	.7171	.8042	.8756
1.9	.3393	.5388	.7442	.8385	.9167
2.0	.3465	.5529	.7696	.8711	.9561
2.1	.3522	.5653	.7933	.9015	.9931
2.2	.3572	.5766	.8150	.9297	1.0287
2.3	.3622	.5867	.8345	.9562	1.0621
2.4	.3662	.5956	.8538	.9809	1.0941
2.5	.3697	.6039	.8696	1.0135	1.1240
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
∞	.4055	.6931	1.0986	1.3863	1.7918

figure was plotted from a conventional (Bouguer anomaly) gravity map of the area. From this last, a maximum residual value of -2.03 mgals was read off. After a number of trials with various values of λ, ρ, and Z_T, it was found that $\lambda = 4$, $\rho = 3$, and $Z_T = 1.415$ miles (7,470 ft.) best reduced the experimental profile data for this dome to one of the curves of Equation (5). Mykawa is believed to be a deep dome (*Oil Weekly*, 1940). However, so far as is known, no well has reached salt in the Mykawa Field.

The two points lying off the assumed curve, in the upper right Figure 10, are believed to be distorted values due to their proximity to neighboring strong anomalies.

TABLE 3

$-C(\rho, u)$ VS. u
AND FOR $\rho = 1.5$, 2, 3, 4, AND 6
(Ref. Equa. 5)

u \ ρ	1.5	2	3	4	6
0	0	0	0	0	0
0.1	.0002	.0006	.0019	.0023	.0036
0.2	.0010	.0025	.0053	.0079	.0123
0.3	.0016	.0055	.0145	.0187	.0264
0.4	.0026	.0093	.0230	.0322	.0450
0.5	.0041	.0139	.0337	.0495	.0698
0.6	.0053	.0189	.0477	.0692	.0970
0.7	.0070	.0245	.0632	.0918	.1289
0.8	.0086	.0305	.0781	.1162	.1651
0.9	.0095	.0360	.0949	.1421	.2026
1.0	.0110	.0416	.1129	.1689	.2345
1.1	.0122	.0469	.1292	.1977	.2869
1.2	.0331	.0526	.1473	.2247	.3308
1.3	.0141	.0574	.1649	.2542	.3734
1.4	.0152	.0620	.1820	.2800	.4220
1.5	.0156	.0666	.1965	.3108	.4670
1.6	.0165	.0703	.2131	.3383	.5134
1.7	.0170	.0736	.2257	.3651	.5621
1.8	.0175	.0771	.2410	.3918	.6086
1.9	.0180	.0797	.2520	.4172	.6544
2.0	.0183	.0830	.2657	.4420	.7000
2.1	.0186	.0842	.2785	.4668	.7452
2.2	.0192	.0882	.2921	.4896	.7908
2.3	.0196	.0888	.3010	.5125	.8354
2.4	.0199	.0915	.3115	.5340	.8779
2.5	.0202	.0930	.3201	.5764	.9204
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
∞	.0225	.1136	.4695	.9774	2.2497

EXAMPLES OF APPLICATIONS OF EQUATION (5)

Example two. Orange Field, Orange County, Texas (Fig. 11)

A residual gravity *vs* radius of residual figure graph was constructed in exactly the same manner as was done for the Mykawa Field. From the graph, a maximum residual value of -2.70 mgals was read off. All of the residual values were divided by this maximum value. Then, from the published information (*Oil Weekly*, 1940) it was found that the depth to the salt was $Z_T = 7{,}120$ ft $= 1.32$ mile. The lateral distances, at which the residual values were obtained, were then divided by Z_T. It was found that the reduced, non-dimensional curve was best duplicated by assuming a frustum with $\lambda = \rho = 4$. The closeness of fit of the experimental

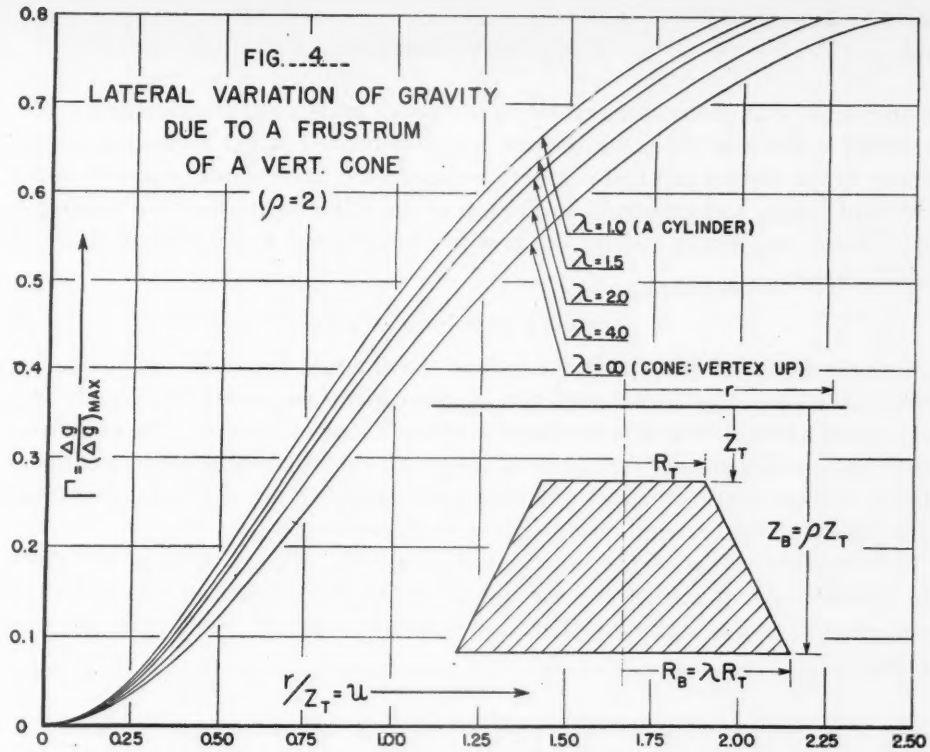

FIG. 4. Lateral variation of residual gravity vs u for $\rho=2$ and for $\lambda=1.0, 1.5, 2, 4$, and ∞.

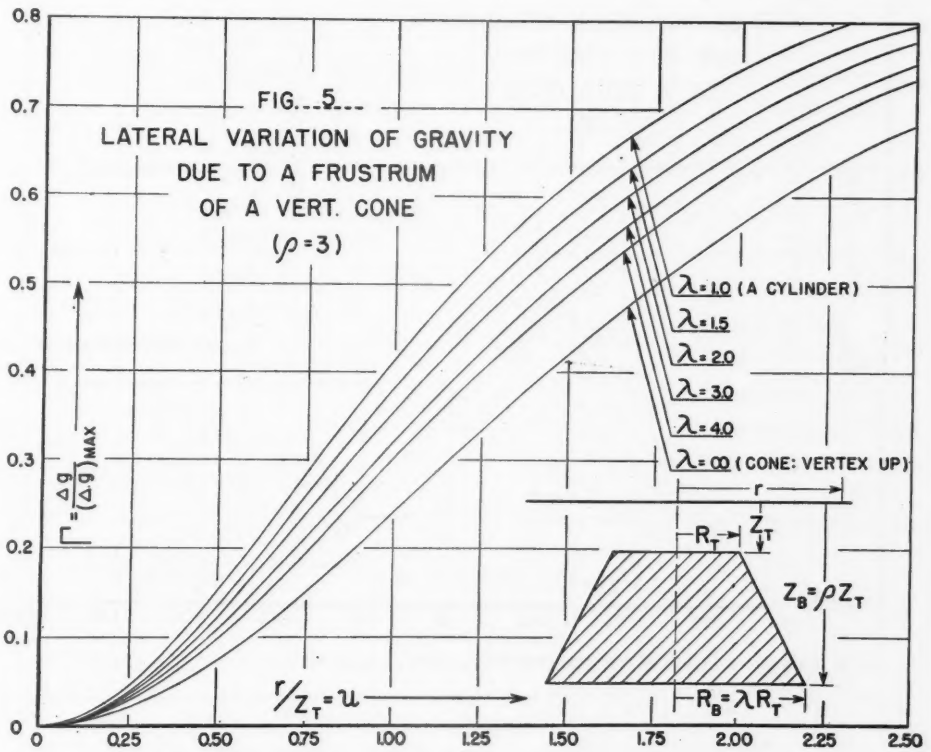

FIG. 5. Lateral variation of residual gravity vs u for $\rho=3$ and for $\lambda=1.0, 1.5, 2, 3, 4$, and ∞.

points upon that of the assumed curve is a rough measure of the closeness of the *assumed* λ and ρ to the actual values. ρ was estimated rather accurately as the depth to the mother salt bed is generally considered to be about 30,000 ft. along the Gulf Coast, and the depth to the top of the salt was known from drilling. λ was chosen empirically to give the best fit, but it seems to be a reasonable and logical value.

SUMMARY AND CONCLUSIONS

Under the assumption that the radii of the frustum are small relative to the depth to its top, the lateral variation of the vertical component of gravity was set up for an elemental disk by use of Newton's Law of Gravity. The effect was summed up (integrated) for the total body and then placed in non-dimensional form. The gravitational effect was then expressed in terms of a ratio of residual gravities. The final general result is given by Equation (5).

Calculated values of the functions $A(\rho, u)$, $B(\rho, u)$, and $C(\rho, u)$ are given in Tables 1, 2, and 3. Figures 2 through 9 are graphs of Equation (5) for various values of λ and ρ, including those for cylinders, upright cones, and inverted cones.

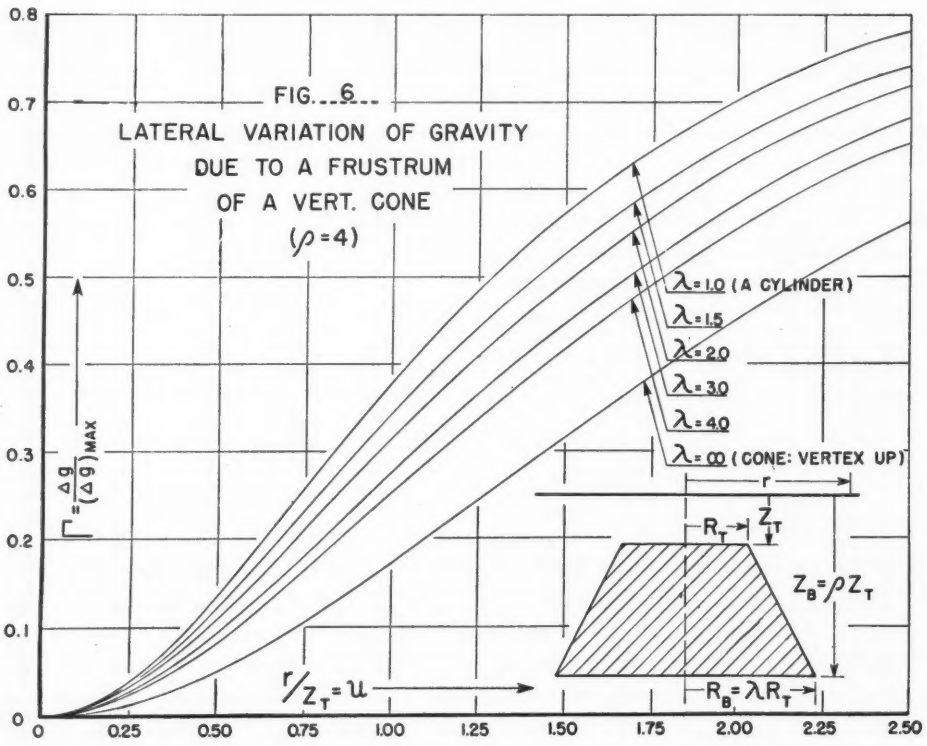

FIG. 6. Lateral variation of residual gravity vs u for $\rho=4$ and for $\lambda=1.0, 1.5, 2, 3, 4$, and ∞.

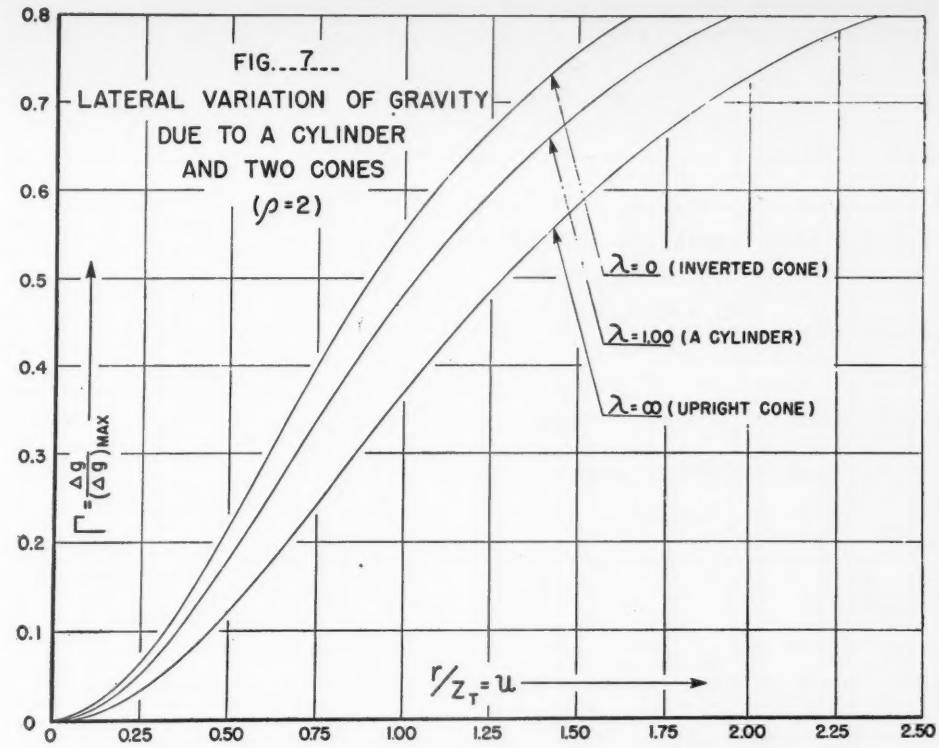

FIG. 7. Lateral variation of residual gravity vs u for $\rho=2$ and for $\lambda=0$ (inverted cone), $\lambda=1.0$ (cylinder), and for $\lambda=\infty$ (upright cone).

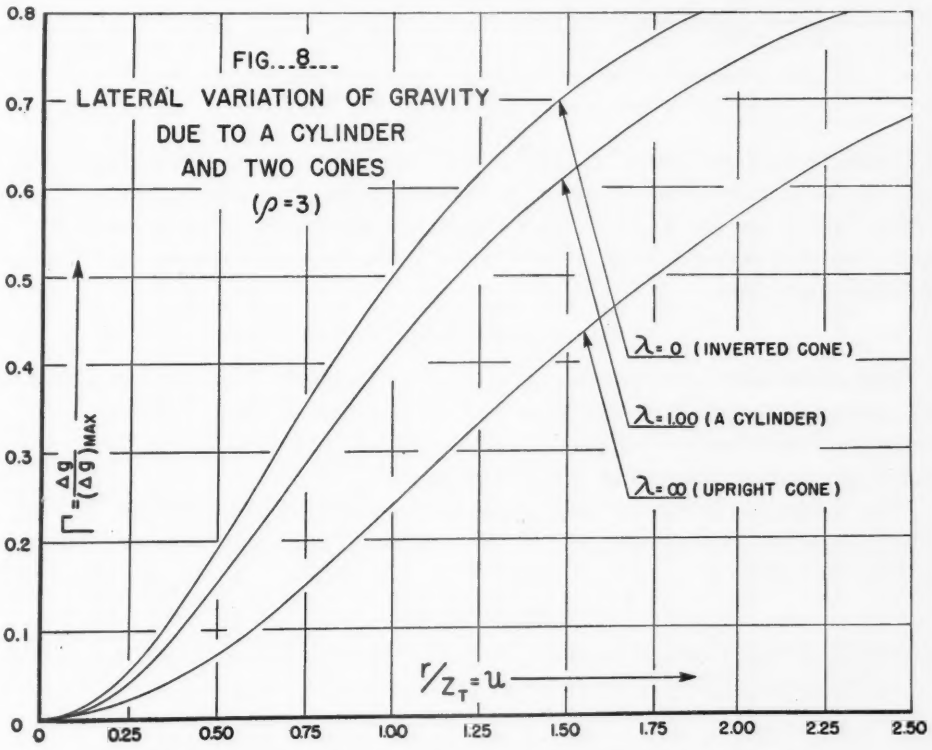

FIG. 8. Lateral variation of residual gravity vs u for $\rho=3$ and for $\lambda=0$ (inverted cone), $\lambda=1.0$ (cylinder), and for $\lambda=\infty$ (upright cone).

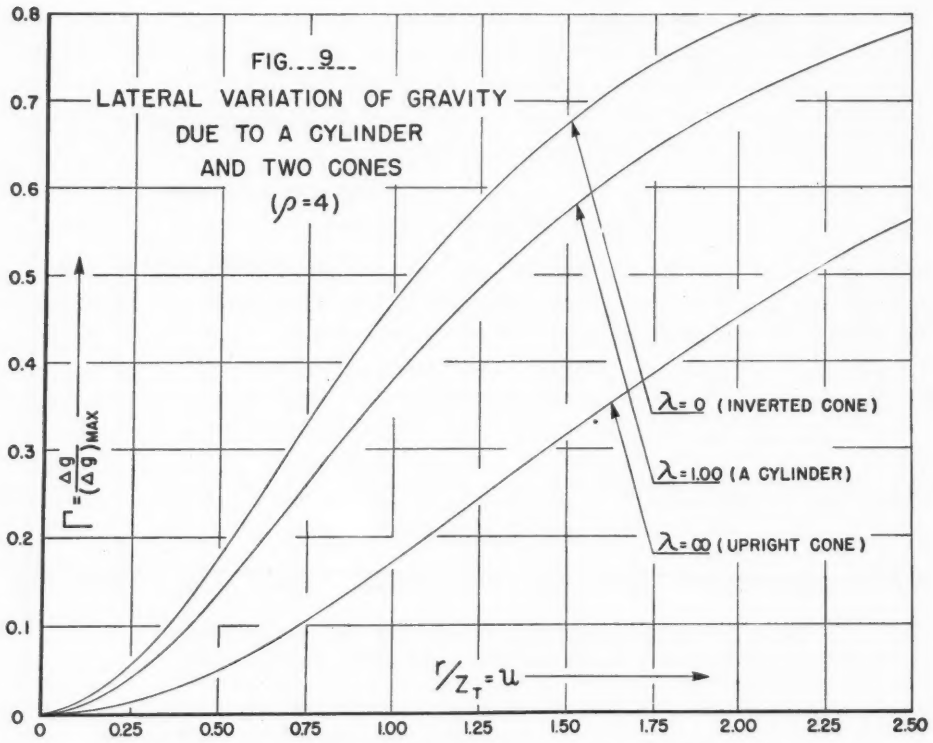

FIG. 9. Lateral variation of residual gravity vs u for $\rho=4$ and for $\lambda=0$ (inverted cone), $\lambda=1.0$ (cylinder), and $\lambda=\infty$ (upright cone).

Then, in Figures 10 and 11, Equation (5) is applied to experimental gravity data on the Mykawa Field, Harris Co., Texas, and the Orange Field, Orange Co., Texas. The conclusion is drawn that, despite the departures of the actual structures from the assumed ones, the correlation between theory and experiment is surprisingly close.

ACKNOWLEDGMENTS

The writer wishes to take this opportunity to thank Mr. Joe King, draftsman, for careful and patient drafting of the figures, Mr. Rayomnd Siever, chief draftsman, for generous cooperation on the project, and Miss Jemes Wyatt for competent and careful typing of the manuscript.

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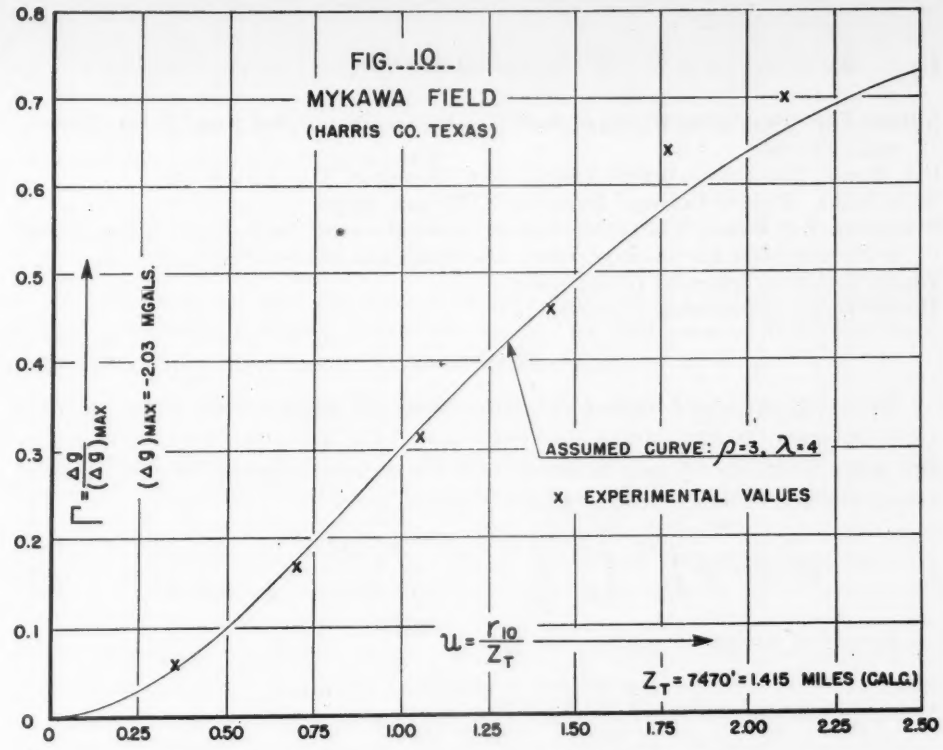

FIG. 10. Comparison of experimental data from Mykawa Field, Harris Co., Texas with assumed theoretical curve derived from Eq. (5) for $\rho=3, \lambda=4$.

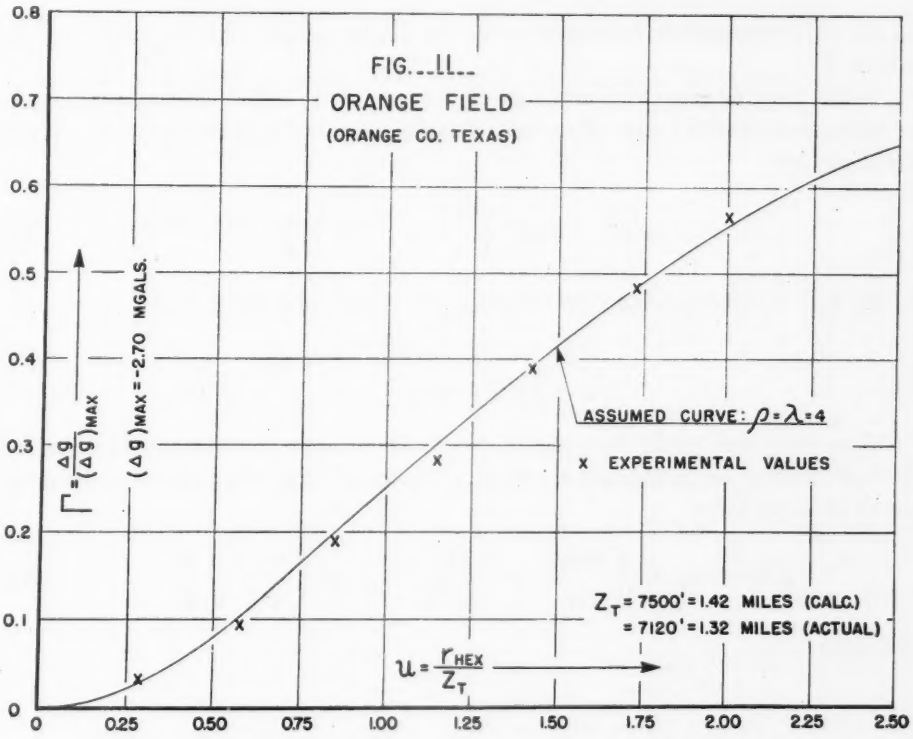

FIG. 11. Comparison of experimental data from Orange Field, Orange Co., Texas with assumed theoretical curve derived from Eq. (5) for $\rho=\lambda=4$.

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APPENDIX

Referring again to Figure 1 and introducing the angle θ as the angle (in plain view) between the line joining the center line of the frustrum to a station x, and any other radial line, it may be shown that the *vertical component* of gravitational attraction due to *any* vertical *cylinder* is given by:

$$g_Z(x) = \gamma\sigma \int_0^{2\pi} \int_{Z_T}^{Z_B} \int_0^R \frac{r dr d\vartheta Z dZ}{(x^2 + Z^2 + r^2 - 2xr\cos\theta)^{3/2}}. \tag{A1}$$

For $x=0$, we have:

$$\begin{aligned} g_Z(0) &= 2\pi\gamma\sigma \int_{Z_T}^{Z_B} \int_0^R \frac{r dr Z dZ}{(Z^2 + r^2)^{3/2}} \\ &= 2\pi\gamma\sigma\{(Z_B - Z_T) - [(R^2 + Z_B{}^2)^{1/2} - (R^2 + Z_T{}^2)^{1/2}]\} \\ &= 2\pi\gamma\sigma Z_T\{(\rho - 1) - [(\mu^2 + \rho^2)^{1/2} - (\mu^2 + 1)^{1/2}]\} \end{aligned} \tag{A2}$$

as the total anomalous attraction over the center of a vertical cylinder of *any* radius R.

It has been shown (Romberg and Barnes, 1948) that the vertical component of attraction over the *edge* of an *infinitely long* vertical cylinder is given, in our notation, by:

$$g_Z(R) = 4\gamma\sigma R\left\{\frac{E(c)}{c} - \frac{\pi}{4}(1/\mu)\right\} \tag{A3}$$

where $E(c)$ is the complete elliptic integral of the Second Kind, and

$$c = [1 + (1/2\mu)^2]^{-1/2}, \tag{A4}$$
$$\mu = (R/Z_T) \equiv \mu_T.$$

Assuming that $g_Z(R)$ for a vertical cylinder of finite length may be obtained in the same manner as that for a vertical cylinder of infinite length, and for a point on its asix, we have

$$g_Z(R) = 4\gamma\sigma R\left\{\left[\frac{E(c_T)}{c_T} - \frac{E(c_B)}{c_B}\right] - (\pi/4)\left(\frac{1}{\mu_T} - \frac{1}{\mu_B}\right)\right\}. \tag{A5}$$

For $\rho \gg 1$.

Using $A(2)$ and $(A5)$ and assuming $Z_T = 1.0$ mile, $Z_B = 2$ miles (i.e., $\rho = 2$), $R = 1.0$ mile, and thus $\mu = 1.0$, we find

$$\Gamma = \frac{\Delta g}{(\Delta g)_{max}} = \frac{g(0) - g(R)}{g(0)} = 1 - \{g(R)/g(0)\} = 0.310.$$

It will be noted that the $(\Delta g)_{max}$ of Equation $A2$ is the true (or rigorous) value. In contrast, the $(\Delta g)_{max}$ used in forming Γ for the figures of this article were determined from Equation (1) for $\mu = 0$, and $\lambda = 1$, or

$$g_z(0) = (\Delta g)_{max} = \pi\gamma\sigma\mu R[1 - 1/\rho] = \pi\gamma\sigma(R^2/Z_T)(1 - 1/\rho)$$

for a *vertical cylinder*, when $\mu \ll 1$. Therefore, to make a fair comparison with the figures of this article, the *true* $(\Delta g)_{max}$ must be changed to *approximate* $(\Delta g)_{max}$, or vice versa. For convenience, the former course will be chosen.

When this conversion is made, $\Gamma = 0.310$ increases to 0.509. Locating this point in Figure 2 at $\mu = 1.00$ and $\Gamma = 0.509$ and comparing with the $\rho = 2$ curve at $\mu = 1.00$, it is seen that the curve gives $\Gamma = 0.480$.

A similar analysis for $\rho = \infty$, $\mu = 1.0$, and $u = 1.0$ gives a *true* $\Gamma = 0.182$ which when converted to approximate $\Gamma = 0.322$. This compares with value of $\Gamma = 0.290$ at $u = 1.0$ for $\rho = \infty$. The conclusion drawn from this is: although the absolute *magnitudes* of these approximate values are considerably in error, nevertheless, the *relative* magnitudes, or *shapes*, differ only slightly from the approximate Γ as given by the curves of the figure (Fig. 2). This would seem to indicate that the approximations of this article are rather close ones for the *lateral variation* of residual gravity.

For *true* Γ, the ordinates of graphs should be *decreased* by the ratio of

$$\frac{2\pi\gamma\sigma Z_T\{(\rho - 1) - [(\mu^2 + \rho^2)^{1/2} - (\mu^2 + 1)^{1/2}]\}}{\pi\gamma\sigma(R^2/Z_T)(1 - 1/\rho)}$$

when μ is *not* small relative to 1.00.

PROPAGATION OF RADIO WAVES OVER A STRATIFIED GROUND*

JAMES R. WAIT†

ABSTRACT

The propagation of vertically polarized radio waves over a horizontally stratified medium is investigated. A general expression for the "wave tilt" is derived for the case of any number of layers with arbitrary properties in each layer. Numerical calculations are carried out for the special case of only two layers which show that the conductivity and dielectric constant variations of the lower layers will affect the magnitude and phase of the wave tilt.

INTRODUCTION

It has been well known that a vertically polarized radio wave will be guided along the interface between the ground and the air. Such a wave was predicted by Zenneck (1) as early as 1907. He showed that the electric vector had a horizontal component, as well as a vertical component, in the direction of the propagation. Wise (2) has shown that the wave radiated from a vertical antenna on a flat conductive earth also has a forward tilt. He also found that the wave tilt for a plane wave at grazing incidence was the same as that from a vertical dipole-type antenna, if the ground was a good conductor. Hack (3), Grossknopf and Vogt (4), and others have applied Zenneck's theory to practical methods of measuring the electrical constants of the ground.

In this paper the general case of a vertically polarized plane wave at oblique incidence on a stratified earth of any number of layers is considered. A general expression for the wave tilt is derived. The two-layer case is studied and curves are given showing the correction to the wave tilt due to conductivity variations of the lower layer.

REFLECTION FROM A STRATIFIED MEDIUM

A plane wave with a time factor $e^{i\omega t}$ is incident at an angle θ on a stratified medium composed of M layers. The electric vector is in the plane of incidence (xz plane). The conductivity, dielectric constant, and magnetic permeability of the layers are σ_m, ϵ_m, and μ_m respectively where m designates the mth layer below the surface. The physical situation is shown in Figure 1. M.K.S. units are used throughout.

The magnetic field H_{my} in any of the regions (0 to M), has only a y component, and is a solution of the wave equation

$$(\nabla^2 - \gamma_m^2) H_{my} = 0, \tag{1}$$

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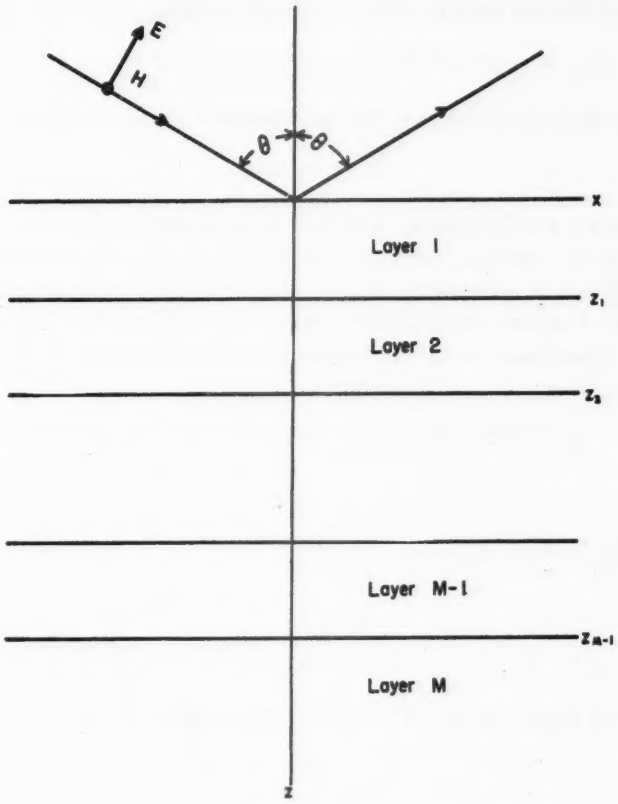

FIG. 1. Coordinate system for the stratified medium of M Layers.

where

$$\gamma_m^2 = i\sigma_m\mu_m\omega - \epsilon_m\mu_m\omega^2.$$

The general solution is therefore of the following form

$$H_{my} = \left[a_m e^{-u_m z} + b_m e^{u_m z}\right] e^{-i\lambda x}, \tag{2}$$

where

$$u_m^2 = \lambda^2 + \gamma_m^2 \text{ and } \lambda \text{ can take any value.}$$

The electric fields E_{mx} and E_{mz} are then given by

$$E_{mx} = -(\sigma_m + i\omega\epsilon_m)^{-1} \frac{\partial H_{my}}{\partial z}, \tag{3}$$

and

$$E_{mz} = (\sigma_m + i\omega\epsilon_m)^{-1} \frac{\partial H_{my}}{\partial x}. \tag{4}$$

The field H_{0y} in the air region is of the following form

$$H_{0y} = (a_0 e^{-\gamma_0 \cos\theta z} + b_0 e^{+\gamma_0 \cos\theta z}) e^{-\gamma_0 \sin\theta x}, \tag{5}$$

where θ is the angle of incidence. The parameter λ must therefore be given by

$$i\lambda = \gamma_0 \sin\theta. \tag{6}$$

The unknown coefficients a_m and b_m can now be found from the boundary conditions that H_{my} and E_{mx} are continuous at each of the interfaces between the layers. In addition it is required that b_m is zero so that only outgoing waves are allowed in the bottom semi-infinite region. If the interface between the m^{th} and $(m+1)^{\text{th}}$ layer is at $z=z_m$ the boundary conditions lead to the following set of equations:

$$a_m e^{-u_m z_m} + b_m e^{u_m z_m} = a_{m+1} e^{-u_{m+1} z_m} + b_{m+1} e^{u_{m+1} z_m}, \tag{7}$$

and

$$\frac{u_m}{\sigma_m + i\omega\epsilon_m}(a_m e^{-u_m z_m} - b_m e^{u_m z_m}) = \frac{u_{m+1}}{\sigma_{m+1} + i\omega\epsilon_{m+1}}(a_{m+1} e^{-u_{m+1} z_m} - b_{m+1} e^{u_{m+1} z_m}). \tag{8}$$

The solution of these equations is carried out to give

$$\frac{b_0}{a_0} = \frac{K_0 - Z_1}{K_0 + Z_1}, \tag{9}$$

where

$$Z_1 = K_1 \frac{Z_2 \cosh u_1 h_1 + K_1 \sinh u_1 h_1}{K_1 \cosh u_1 h_1 + Z_2 \sinh u_1 h_1},$$

$$Z_2 = K_2 \frac{Z_3 \cosh u_2 h_2 + K_2 \sinh u_2 h_2}{K_2 \cosh u_2 h_2 + Z_3 \sinh u_2 h_2},$$

$$Z_{M-1} = K_{M-1} \frac{K_M \cosh u_{M-1} h_{M-1} + K_{M-1} \sinh u_{M-1} h_{M-1}}{K_{M-1} \cosh u_{M-1} h_{M-1} + K_M \sinh u_{M-1} h_{M-1}},$$

and

$$K_m = u_m/(\sigma_m + i\epsilon_m\omega)$$

The ratio b_0/a_0 can be interpreted as a reflection factor for plane waves, with a propagation constant u_0, incident normally on the surface of a stratified region whose layers of thickness h_m have a propagation constant u_m and characteristic wave impedance K_m.

The "wave tilt" is now defined by

$$W = \left.\frac{E_{0x}}{E_{0z}}\right]_{z=0}, \tag{10}$$

so that

$$W = \left.\frac{E_{1x}/H_{1y}}{E_{0z}/H_{0y}}\right]_{z=0} = \frac{i\omega\epsilon_0 Z_1}{\gamma_0 \sin\theta}. \tag{10a}$$

When the ground is homogeneous of conductivity σ_1 and dielectric constant ϵ_1 the wave tilt becomes

$$W_0 = \frac{i\omega\epsilon_0 K_1}{\gamma_0 \sin\theta} \tag{11}$$

which is the value given by Wise (2).

A certain simplification of the general case can be made if the following inequality is valid

$$\left|\gamma_0^2/\gamma_m^2\right| \ll 1 \quad \text{for} \quad m > 0;$$

the function $u_m h_m$ is then given by

$$u_m h_m = \gamma_m h_m \left[1 - \frac{\gamma_0^2}{\gamma_m^2}\sin^2\theta\right]^{1/2} \approx \gamma_m h_m;$$

also

$$K_m = u_m/(\sigma_m + i\omega\epsilon_m) \approx \gamma_m/(\sigma_m + i\omega\epsilon_m).$$

The approximations are usually justified for radio broadcast frequencies or lower and normal values of the ground constants (5). The wave tilt W then becomes, letting θ tend to 90°:

$$W = W_0 Q,$$

where $W_0 = \gamma_0/\gamma_1$ is the wave tilt for the homogeneous earth. Q is the amount this wave tilt is modified by the presence of horizontal stratification and is given by

$$Q = Z_1/K_1.$$

TWO LAYER CASE

The values of Q for a horizontally stratified two layer earth will be calculated for a selected range of the parameters involved. The value of M is now equal to 2, so that the ground is represented as a stratum of thickness h_1, conductivity σ_1 and dielectric constant ϵ_1 below which the medium is semi-infinite with conductivity σ_2 and dielectric constant ϵ_2. The magnetic permeability is taken as μ for the whole space. The correction factor Q to the wave tilt is then

$$Q = \frac{K_2 \cosh \gamma_1 h_1 + K_1 \sinh \gamma_1 h_1}{K_1 \cosh \gamma_1 h_1 + K_2 \sinh \gamma_1 h_1} . \tag{12}$$

It is convenient now to introduce the following substitutions

$$V = (\sigma_1 \mu \omega)^{1/2} h_1$$

and

$$\delta_1 = \epsilon_1/\sigma_1\omega, \qquad \delta_2 = \epsilon_2/\sigma_2\omega.$$

The argument of the hyperbolic functions is then

$$\gamma_1 h_1 = V(1 + \delta_1^2)^{1/4} e^{i[(\pi/2) - (\tan^{-1}\delta_1]/2)}.$$

The factor Q is plotted in Figure 2 as a function of V, for the case where dis-

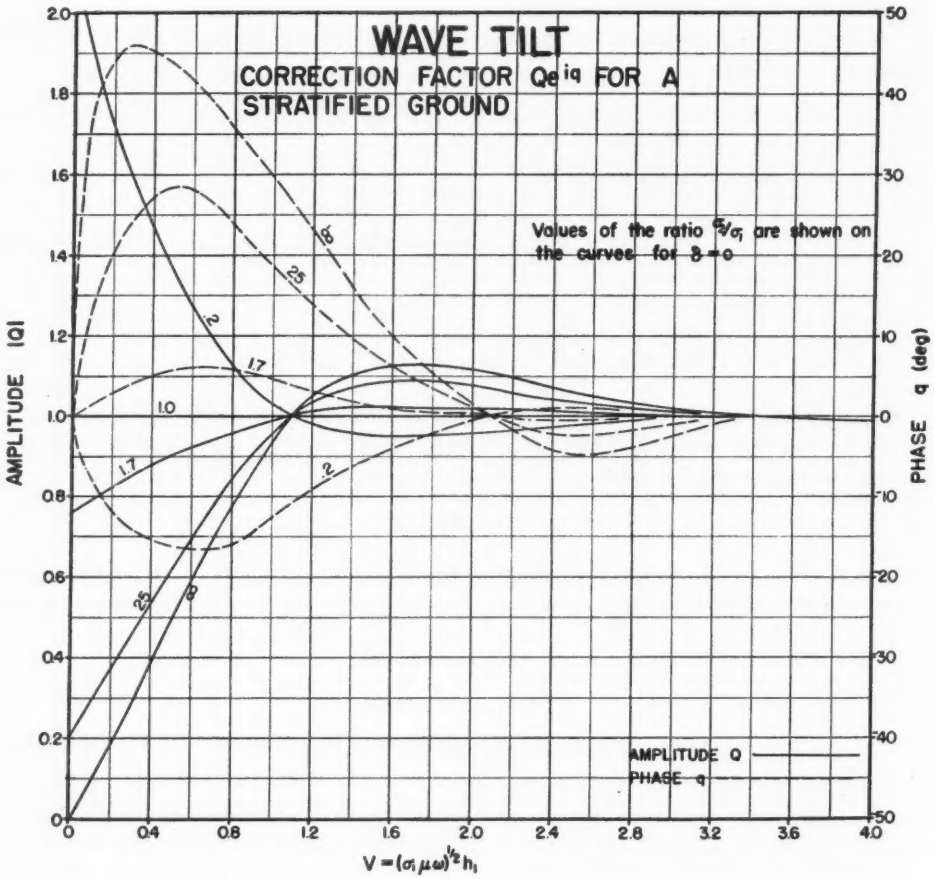
WAVE TILT
CORRECTION FACTOR Qe^iq FOR A STRATIFIED GROUND
Values of the ratio ε/σ₁ are shown on the curves for δ = 0
AMPLITUDE Q
PHASE q
AMPLITUDE |Q|
PHASE q (deg)
V = (σ₁μω)^½ h₁

FIG. 2. The correction to the wave tilt for a two layer structure with a conductivity contrast.

placement factors δ_1 and δ_2 are much less than one. Various values of the conductivity ratio σ_2/σ_1 are shown on the curves.

When the displacement factors δ_1 and δ_2 become appreciable the shape of the curves for Q are modified slightly. This is shown in Figure 3 when δ_1 and δ_2 are taken to be equal and designated by δ, and have the values 0.0, 0.1, and 0.3. The conductivity ratio σ_2/σ_1 is taken as 25. It is apparent that if δ_1 and δ_2 are of the order of 0.1 or less, the Q curves are indistinguishable from the curves where δ_1 and δ_2 are zero.

An example may be quoted which illustrates the order of magnitude of the quantities involved by employing the following typical values:

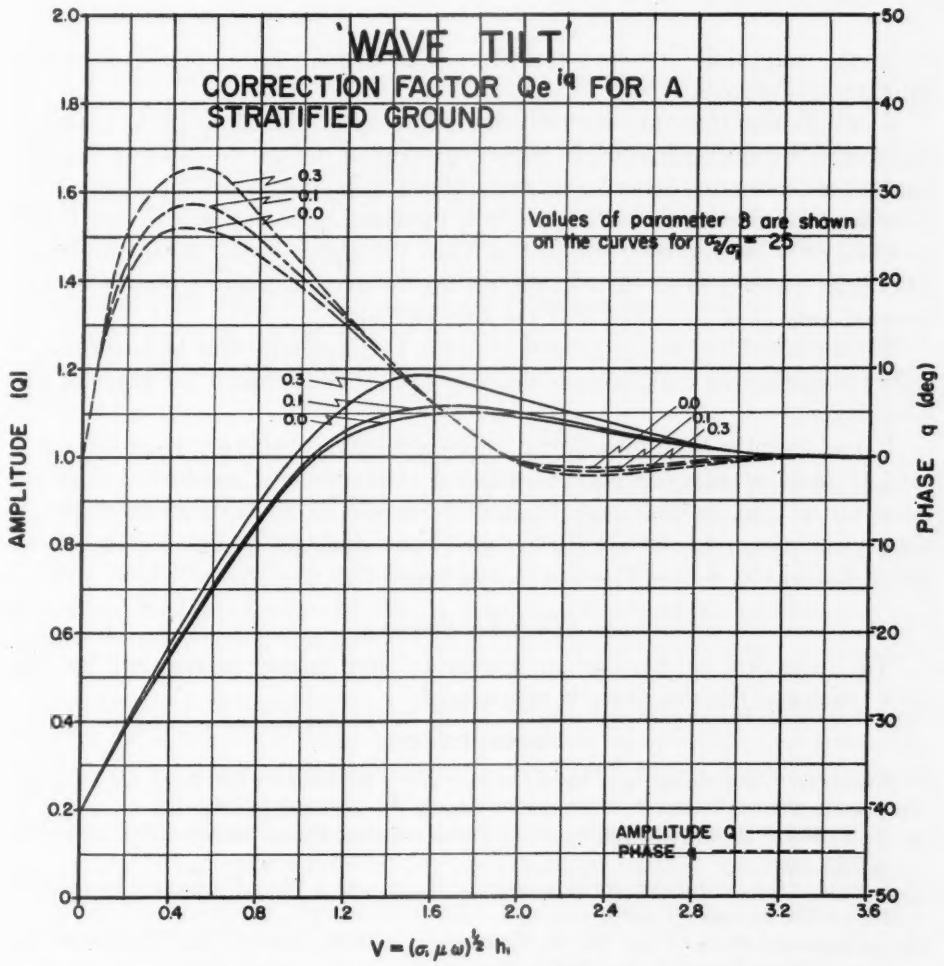

FIG. 3. The correction to the wave tilt for a two layer structure when the dielectric constants are considered.

Frequency,	$f=\omega/2\pi=125$ Kilocycles/sec
Upper Layer Conductivity,	$\sigma_1=10^{-2}$ mhos/metre
Dielectric Constant of Air,	$\epsilon_0=8.854\times10^{-12}$ farads/metre
Dielectric Constant of Ground	$\epsilon_1=10\epsilon_0$
Displacement Factor,	$\delta_1=0.0069$
Magnetic Permeability	$\mu=4\pi\times10^{-7}$ henries/metre

The Parameter V is then given by $V=h/10$ metres so that the abcissa of Figure 2 is, for this special case, equal to the depth of the upper layer in tens of metres. The wave tilt W for the two layer structure is then

$$W = W_0 Q = .082\,|\,Q\,|\,/41.1^\circ + q,$$

where the amplitude $|Q|$ and the phase q in degrees are obtained from the ordinates in Figure 2.

It is thus seen that the wave tilt at a frequency of 125 kilocycles is modified appreciably by discontinuities in the substratum at depths down to 20 metres. For higher-conducting lower layers at depths of 10 metres or less the wave tilt W is reduced in magnitude and the phase is increased. The opposite is true if the lower layer is more poorly conducting than the upper layer. When the lower layer is at depth greater than 10 metres the connection factor Q oscillates and becomes very close to unity, after the first oscillation.

Other examples could easily be illustrated. It is generally seen however that a higher frequency or a higher conductivity or both will reduce the effect of the lower layers.

It has recently been found that a similar analysis can be carried out for a vertical radiator situated on the surface of the stratified conductor. The attenuation of the ground wave at low frequencies is then determined by an effective propagation constant γ_e related to the propagation constant γ_1 of the upper stratum by $\gamma_e \cong \gamma_1/Q$ where it is assumed that $|\gamma_e|^2 \gg |\gamma_0|^2$.

ACKNOWLEDGMENT

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LIMITATIONS ON RESISTIVITY METHODS AS INFERRED FROM THE BURIED SPHERE PROBLEM*

ROBERT G. VAN NOSTRAND†

ABSTRACT

The study of resistivity surveys over buried spheres is facilitated by the use of a bipolar coordinate system. Without solving the incident potential problem exactly, the author obtains an exact solution for the apparent resistivity as measured by the Wenner configuration of electrodes situated directly over a buried conducting sphere. From a study of depth profiles over a set of spheres buried at different depths, it is concluded that one cannot expect to find by direct current methods a sphere buried to a depth greater than the radius of the sphere. This result is generalized to include bodies of more arbitrary shape.

It is desirable in any geophysical work that one realizes the limitations of the techniques which he is using. With that thought in mind, the study of buried conducting spheres is used as a vehicle to determine a specific limitation which exists in the realm of direct current prospecting.

Apparently, the only previous studies of buried spheres have been made by Russian workers (Lipskaya, 1949). The present paper uses a somewhat different technique to arrive at a solution; and further, the formal mathematics is carried over to a specific result directly applicable to field work.

A related article, on the electrical investigation of buried ore bodies through the use of existing bore holes, has recently been published in this journal (Seigel, 1952).

BIPOLAR COORDINATES

In order to investigate situations in which a spherical mass of foreign material is completely enclosed by an otherwise homogeneous earth, it is necessary to resort to bipolar coordinates (Fig. 1a). If the right half of that diagram, consisting of two sets of coaxial circles, is rotated about the polar axis, it will generate two orthogonal families of surfaces; the third required family is the set of half planes whose common intersection is the polar z-axis. The azimuthal angle ϕ is the parameter of this set of planes.

The family of spheres whose centers lie on the z-axis is characterized by the parameter σ which varies from negative to positive infinity. The first pole is located at the point on the polar axis for which $z=b$; and, at this point, σ is positive and infinite. The spheres surrounding this point increase in radius as σ decreases until finally the equatorial xy-plane is the surface upon which σ is everywhere zero. At the second pole, where $z=-b$, σ is negatively infinite. The progressively

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larger spheres surrounding this point represent increasing values of σ. Thus, the range of σ is such that $-\infty < \sigma < \infty$.

The centers of these spheres may most easily be located by a simple geometric device. Let C be the center of a specific sphere $\sigma = \sigma_1$ (Fig. 1b); A and B are the positive and negative poles respectively; and D is either intersection of the sphere with the polar axis. One can then write the relationship $\overline{CA}:\overline{CD} = \overline{CD}:\overline{CB}$, which

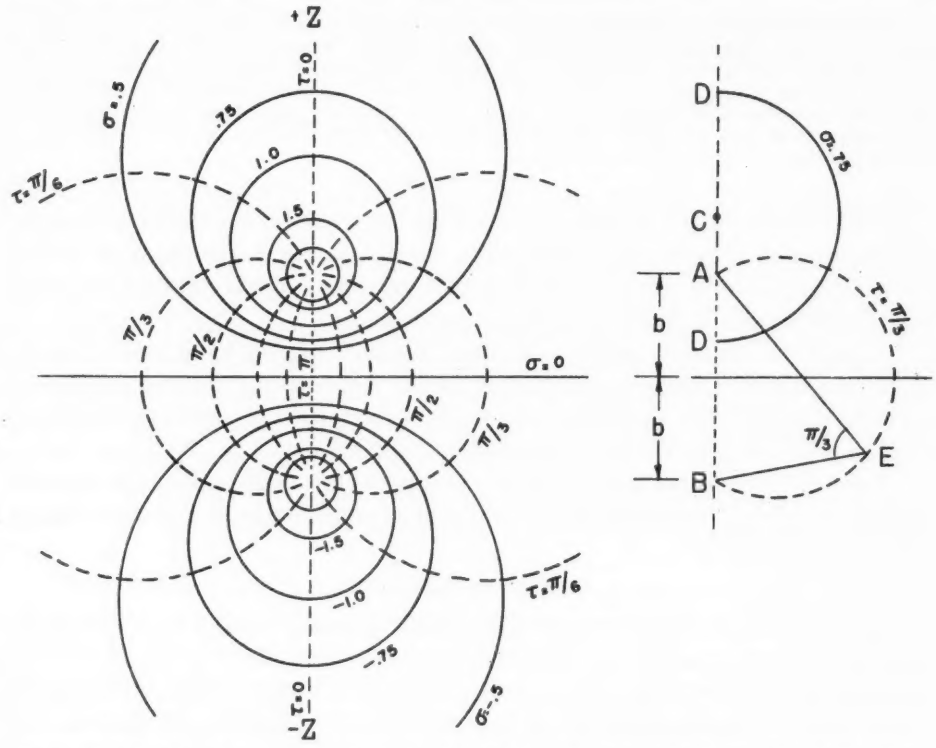

FIG. 1. Bipolar Coordinates. a. As shown in the meridian plane $\phi = 0$. b. Geometric relationships.

condition establishes uniquely the center of the sphere. Further, it can be shown that $\sigma = \ln(\overline{BD}/\overline{AD})$. These relationships completely describe a given sphere in the family whose centers lie on the z-axis.

One can describe uniquely the second family of surfaces through the use of a standard theorem which states that the angle subtended by a chord at any point on the segment of a circle, cut by that chord, is a constant. Thus, the angle subtended by the line $\overline{AB}$ at any point on the surface designated by a given value of τ is equal to τ itself. Since only the right half of the diagram has been rotated, the surfaces generated are not in general spheres, but instead are surfaces of degree four which Hobson designates as spindles.

The smallest sphere which can possibly pass through the two points $z = b$ and $z = -b$ has its center at the origin and is the surface $\tau = \pi/2$. Finally, the portion

of the polar axis above $z=b$ and below $z=-b$ is the two segment line $\tau=0$, that portion lying between $z=b$ and $z=-b$ being the locus of points for which $\tau=\pi$.

Since survey measurements in a geophysical project are always made on a linear scale, it is necessary that one be able to convert bipolar coordinates to field measurements. In this respect, the following transformations from bipolar coordinates to rectangular coordinates are useful:

$$x = \frac{b \sin \tau \cos \theta}{\cosh \sigma - \cos \tau}, \quad y = \frac{b \sin \tau \sin \phi}{\cosh \sigma - \cos \tau}, \quad z = \frac{b \sinh \sigma}{\cosh \sigma - \cos \tau}. \tag{1}$$

THE SOLUTION OF LAPLACE'S EQUATION

The basic physical problem to be solved is the determination of the potential function due to a point source of current in the vicinity of two spheres whose resistivity differs from that of the surrounding material. It can be shown that this potential function obeys Laplace's equation everywhere except at the position of the point source. In terms of the variables σ, τ, and ϕ, Laplace's equation is written as (MacRobert):

$$\frac{\partial}{\partial \sigma}\left[\frac{b \sin \tau}{\cosh \sigma - \cos \tau} \frac{\partial U}{\partial \sigma}\right] + \frac{\partial}{\partial \tau}\left[\frac{b \sin \tau}{\cosh \sigma - \cos \tau} \frac{\partial U}{\partial \tau}\right] + \frac{b}{\sin \tau(\cosh \sigma - \cos \tau)} \frac{\partial^2 U}{\partial \phi^2} = 0. \tag{2}$$

A separation of variables can be effected through a change of the dependent variable. To this end, let: $U=(\cosh \sigma - \cos \tau)^{1/2} W$ and assume a solution in the form of: $W=S(\sigma)T(\tau)\Phi(\phi)$. In terms of the new dependent variables, the equation becomes:

$$\frac{1}{S}\left[\frac{d^2 S}{d\sigma^2} - \frac{1}{4}\right] + \frac{1}{T \sin \tau} \frac{d}{d\tau}\left[\sin \tau \frac{dT}{d\tau}\right] + \frac{1}{\Phi \sin^2 \tau} \frac{d^2 \Phi}{d\phi^2} = 0. \tag{3}$$

Two parts of (3) may be equated to separate and independent constants. First let:

$$\frac{d^2 \Phi}{d\phi^2} + m^2 \Phi = 0, \tag{4}$$

for which the solution is known to be:

$$\Phi_m = A_m \cos m\phi + B_m \sin m\phi. \tag{5}$$

In order to keep this solution single valued, m must be an integer but may take on any positive value. A_m and B_m are arbitrary constants depending only on the value of m.

The second separable part of (3) is that involving S, which when set equal to a constant yields:

$$\frac{d^2S}{d\sigma^2} - [n(n+1) + 1/4]S = 0. \tag{6}$$

A solution to (6) can be obtained through the methods of ordinary differential equations; whence one finds that:

$$S_n = C_n e^{(n+1/2)\sigma} + D_n e^{-(n+1/2)\sigma}. \tag{7}$$

Here, C_n and D_n are arbitrary constants depending only on the value of n which at this point is yet unrestricted.

When the constants m and n are introduced into (3), through the use of (4) and (6), one obtains:

$$\frac{1}{\sin\tau}\frac{d}{d\tau}\left[\sin\tau\frac{dT}{d\tau}\right] + \left[n(n+1) - \frac{m^2}{\sin^2\tau}\right]T = 0, \tag{8}$$

which is recognized as being the associated Legendre equation whose solution is:

$$T_{mn} = E_{mn}P_n{}^m(\cos\tau) + F_{mn}Q_n{}^m(\cos\tau). \tag{9}$$

$P_n{}^m()$ and $Q_n{}^m()$ are the associated Legendre polynomials of the first and second kind respectively. As a consequence of this solution, n is restricted to positive, integral values and m is further restricted to values less than, or equal to, n. Actually, all regions in which this solution is useful contain points at which τ is 0 or π. Since the Legendre polynomials of the second kind become infinite at such points, it may be excluded even from the general solution, and the arbitrary constant E_{mn} can be absorbed in the general solution by C_n and D_n.

Finally, one obtains for the general solution of (2) the sum of all possible products formed for the different allowed values of m and n:

$$U = (\cosh\sigma - \cos\tau)^{1/2}\sum_{n=0}^{\infty}\sum_{m=0}^{n}[A_m\cos m\phi + B_m\sin m\phi] \cdot [C_{mn}e^{(n+1/2)\sigma} + D_{mn}e^{-(n+1/2)\sigma}]P_n{}^m(\cos\tau). \tag{10}$$

It is seen that the factor multiplying the series becomes infinite as σ approaches infinity near the points $z=b$ and $z=-b$. However, further examination shows that there is always a term in the summand which goes to zero, at the same points, in such a way that the solution remains finite but does not in general vanish.

SPECIAL CASE OF CONDUCTING SPHERES

A simple, but very instructive, case which can be treated in bipolar coordinates is that of a resistivity survey in the neighborhood of a buried conducting sphere. From a study of this problem, one is able to learn something of the limits of the electrical methods of prospecting.

Before attacking the boundary value problem, one must have an expression,

in terms of the functions in(10), for the reciprocal of the distance between two points. The desired expansion has been given by Hobson as:

$$\frac{1}{r} = \frac{1}{b}(\cosh \sigma_0 - \cos \tau_0)^{1/2}(\cosh \sigma - \cos \tau)^{1/2}$$

$$\cdot \sum_{n=0}^{\infty} \sum_{m=0}^{n} (2 - \delta_{0m}) \frac{(n-m)!}{(n+m)!} e^{\pm (n+1/2)(\sigma_0 - \sigma)} P_n{}^m(\cos \tau_0) P_n{}^m(\cos \tau) \cos m\phi, \quad (11)$$

where the coordinates of the reference point are $(\sigma_0, \tau_0, 0)$ and those of the second point are (σ, τ, ϕ). The upper and lower signs in the exponential apply according as σ_0 is less than or greater than σ respectively. The symbol δ_{0m} is the kronecker delta which equals one when m is 0 and vanishes otherwise.

One now considers the specific situation in which the material within the spheres $\sigma = \sigma_1$ and $\sigma = -\sigma_1$ has comparatively low resistivity, which is assumed to be zero. The material exterior to both spheres has the uniform resistivity ρ. Further, let a point source of current of strength I be located at the point $(0, \tau_0, 0)$. If this point source of current were located in an infinite medium of resistivity ρ, the potential at any point in space would be given by $I\rho/4\pi r$ where r is the distance between the source and the point in question. In this problem, r must be expressed according to (11).

In addition, the potential function must contain a term due to the presence of the spheres. Such a term is given by the expression (10) which may be simplified in the present problem. First, since the source lies on the plane $\phi = 0$, the solution must be symmetrical in ϕ and the sine term may be discarded. Secondly, since the source lies on the midplane $\sigma = 0$ between the spheres, this plane must be a plane of symmetry and the coefficients of both exponential terms must be identical. With these considerations in mind, we now write the complete potential function as:

$$U = (\cosh \sigma - \cos \tau)^{1/2} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left\{ \frac{I\rho}{4\pi b} (\cosh \sigma_0 - \cos \tau_0)^{1/2} (2 - \delta_{0m}) \right.$$

$$\cdot \frac{(n-m)!}{(n+m)!} e^{\pm (n+1/2)(\sigma_0 - \sigma)} P_n{}^m(\cos \tau_0)$$

$$\left. + A_{mn}[e^{(n+1/2)\sigma} + e^{-(n+1/2)\sigma}] \right\} P_n{}^m(\cos \tau) \cos m\phi. \quad (12)$$

The one arbitrary constant A_{mn} can be determined by applying a single boundary condition. Within the spheres, the potential has some constant value, as yet to be determined but which for the moment is considered to be zero. If the potential within the spheres were zero, as assumed, the potential function (12) could be equated to zero at the surface $\sigma = \sigma_1$. From this condition then a tentative value is obtained for A_{mn} and substituted back into (12).

At this point, it is appropriate to take cognizance of the actual geophysical problem in which a current electrode is placed on the surface of a semi-infinite medium rather than within an infinite medium. In the above problem, it is clear that no current crosses the midplane $\sigma = 0$ between the two spheres. Therefore, this plane may be used to represent the surface of the earth, in which case the upper half of space including the sphere $\sigma = \sigma_1$ is discarded. In order to make the solution numerically correct, one then multiplies by two the potential function which has been derived for infinite space.

Therefore, a potential function for a point source of current on the surface of the earth in the vicinity of a buried conducting sphere is given by:

$$U' = \frac{I\rho}{2\pi}\left[\frac{1}{r} - \frac{2}{b}(1 - \cos\tau_0)^{1/2}(\cosh\tau - \cos\tau)^{1/2} \cdot \sum_{n=0}^{\infty}\sum_{m=0}^{n}(2 - \delta_{0m})\frac{(n-m)!}{(n+m)!}\frac{P_n^m(\cos\tau_0)P_n^m(\cos\tau)}{1 + e^{-(2n+1)\sigma_1}}\cos m\phi\right], \qquad (13)$$

Where the prime indicates that the potential is incorrect because one has not taken into consideration the true constant potential of the conducting sphere. The previous expansion used for $1/r$ is not included here for it is required only in applying the boundary conditions and not in computations.

DEPTH PROFILES OVER BURIED SPHERES

An expression is now obtained for the apparent resistivity as measured by the Wenner configuration of electrodes oriented along the line $\phi = 0$, π and symmetrically situated with respect to the buried sphere as shown in Figure 2a. The triangles represent current electrodes and the rectangles the potential electrodes. The distance between adjacent electrodes is a.

Note that the value of τ_0 is the same for both current stakes as is the value of τ for both potential electrodes. This symmetry permits one to use (13) as it stands without ever knowing explicitly the value of the constant potential within the conducting sphere. To explain this fact more fully, we resort to the electrostatic analogy—or, more exactly, to a series of electrostatic analogies.

Consider first a point charge in the vicinity of a grounded sphere. It is well known that a charge distribution is induced on the surface of the sphere, that the potential everywhere on that surface is zero, and that the effect of the induced charge on the potential in the exterior space can be described in terms of a single image located at the point within the sphere inverse to the position of the true point charge. If a point charge is brought near a grounded sphere, a second image must be introduced at the center of the sphere. The second image has the same strength as the first, but has the opposite sign. Its purpose is to maintain constant total charge on the sphere.

A point charge situated equidistant from two equivalent, grounded spheres bears analogy to the geophysical problem as it was solved above. In the electro-

static case, one may obtain an expression for the potential in the exterior region. Now, if the same problem be considered with insulated spheres, an additional expression must be provided to account for the fact that the total charge on each sphere has to remain constant—or, in other words, to raise the potential of each sphere to its proper value in the field. A charge placed at the center of one sphere could produce the correct effect for that sphere; but, at the same time, it would adversely affect the second sphere. Therefore, as in the study of the effect of two charged spheres on each other (Smythe), one is compelled to use an infinite

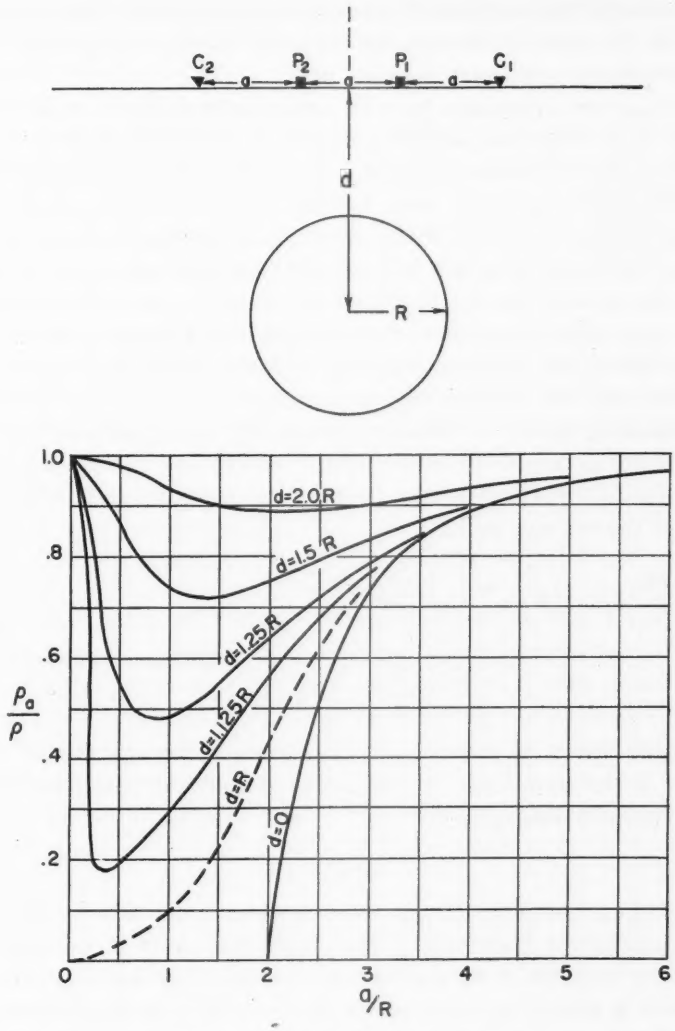

FIG. 2. a. Wenner configuration over buried sphere. b. Depth profiles over spheres buried at different depths.

series of images. The point of the argument is that all of these images lie on the line joining the centers of the spheres, the net effect on the potential in the exterior region being symmetrical with respect to that axis.

If this argument is carried over into the direct current problem under consideration, it means that the term or terms, which have been omitted from (13) because the potential of the sphere was considered to be zero, have an equal effect on the two potential electrodes. The fact that such a term exists cannot be determined by a measurement of the potential difference between these electrodes. Thus, the expression in (13) is usable in the present investigation as though it were the correct one. However, it is to be noted that this argument holds only in the present case and should not be carried further into situations in which the present symmetry does not exist.

In obtaining an expression for the apparent resistivity, it is seen in this symmetrical case that the potential difference between P_1 and P_2 (Fig. 2a) due to C_2 is exactly the same as that due to C_1. Therefore, one considers only the potential difference due to C_1 and doubles the resulting expression. Further, since the coordinates of P_1 and P_2 are the same except for the angle ϕ, the potential difference between these two points is the difference between two summations which are alike except that one contains the factor $(-1)^m$.* Thus, the terms for which m is even vanish and those for which m is odd appear with an additional factor of 2. When the distance between adjacent electrodes is given by a, the difference between $1/r_1$ and $1/r_2$ is given by $1/2a$.

If the resulting potential difference is equated to a corresponding expression $(I\rho_a/2\pi a)$ for the potential difference were the earth assumed to be homogeneous, one can solve the equation for the ratio of the apparent resistivity to the true resistivity of the country rock:

$$\frac{\rho_a}{\rho} = 1 - \frac{2a}{b}(1 - \cos\tau_0)^{1/2}(1 - \cos\tau)^{1/2} \cdot \sum_{n=1}^{\infty} \sum_{m=1,\text{odd}}^{n} \frac{(n-m)!}{(n+m)!} \frac{P_n^m(\cos\tau_0)P_n^m(\cos\tau)}{1 + e^{-(2n+1)\sigma_1}} . \qquad (14)$$

As a reminder, it is pointed out that τ_0 is the coordinate of the current electrode; τ is the coordinate of the potential electrode; and, $\sigma = -\sigma_1$ describes the surface of the buried sphere.

RESULTS

A series of curves (Fig. 2b) has been prepared from data based on (14). The ratio of the apparent resistivity to the actual resistivity of the country rock is plotted as the ordinate; and, the ratio of the electrode separation to the radius of the sphere is shown as the abscissa. Each curve represents data for a given

* Because $\cos(0) = 1$ and $\cos(m\pi) = (-1)^m$.

buried, conducting sphere, the depth to the center of the sphere also being expressed in terms of the radius of the sphere. Thus, the graph is dimensionless and may be applied to any specific case if the correct scale is introduced.

Two curves of the set shown are not based on (14). That for the hemisphere ($d=0$) is based on the electrostatic analogy which may be found in any intermediate text on electricity (for example, Slater and Frank); that for the buried sphere which is tangent to the earth's surface ($d=R$) has been estimated from the shapes of the other curves shown.

When the sphere is definitely buried, the curve starts for small electrode separation with ρ_a/ρ equal to one. Each curve displays a minimum, which represents the electrode separation at which the sphere produces a maximum effect on the results; and, then each curve trends upward to approach one asymptotically at large electrode separations.

On the other hand, if the sphere is truncated at all by the earth's surface, the corresponding curve starts at zero at the electrode separation equal to the diameter of the circle of truncation, and then rises continuously to approach one asymptotically. The curve for the hemispherical case is one limiting example of this type. The curve representing the other limiting case, that in which the sphere is tangent to the surface of the earth, starts at the origin.

It should be noted that the first five curves in the diagram actually cross the hemisphere curve in the range of the electrode separation between 3.5 and 6, but do not cross each other. This fact implies that the buried spheres have a greater effect at large electrode separations than does the hemisphere; which phenomenon is related to the volume of foreign material which is present in the field and to the ratio of this volume to the volume of space in which the current density is arbitrarily appreciable.

The principal geophysical value of these curves stems from the fact that the disturbing body of zero resistivity has a maximum effect on the measurement of the apparent resistivity for a given geometrical relationship. This fact has been verified, for the case in which the electrodes do not actually fall within the disturbing material, even when comparison is made with a body of infinite resistivity. Of course, the assumption is always valid, even if the electrodes do fall within the disturbing body, when the resistivity of the disturbing body is less than that of the surrounding material.

The first useful implication lies in the maximum depth at which one can expect to locate a spherical mass of material by direct current methods. The curve for which the depth to the center of the sphere is twice the radius of the sphere, has a minimum for which the apparent resistivity varies only ten percent from the regional value of the true resistivity. Therefore, one is led to the assumption that it would not be safe to depend on finding such a feature when its depth is greater than this value. This result, being in the nature of a guiding principle rather than a hard fact, may safely be extended to bodies of arbitrary shape provided that the variation between the maximum and minimum dimensions

is not too extreme; a factor of two might well be permissible. In such a case, a maximum depth to the center of the body equal to the mean linear dimension of the body would appear to be in order. Since this rule has been based on the limiting case of a conducting sphere, the ability of resistivity methods to locate bodies presenting less than extreme resistivity contrasts would be considerably reduced below the standard set above.

It is recognized that the limits discussed are based only on the direct affects of the disturbing body. In some instances, it may happen that certain near surface structural features exist over the disturbing body, and that the detection of such features through electrical means could yield information concerning the presence of a body buried deeper than the above rule permits. A typical associ-

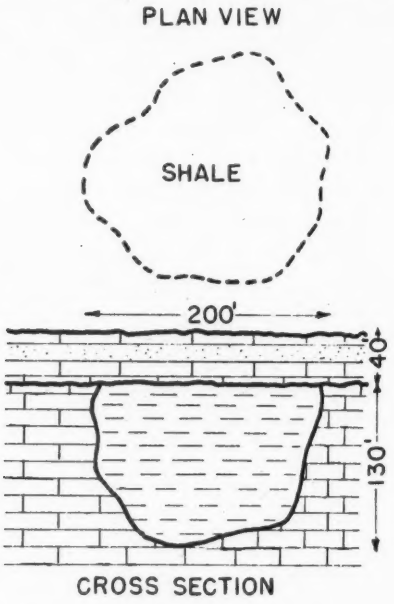

FIG. 3. Example of buried body.

ated structure might be a system of fractures due to differential compaction of overlying beds.

Because the maximum anomaly in the horizontal traverse occurs when the configuration is directly above the foreign mass, the discussion applies in any direct current technique of prospecting.

The second use of these curves, applicable to horizontal profiling, is in the choice of the proper electrode separation in a given situation. When one enters a region to perform a survey, he is generally advised by geologists as to the approximate depth at which he should find a certain geologic condition. Suppose, for example, that ore is known to be associated with clay filled sinks about 200 feet in diameter and 130 feet in vertical dimension, located in an ancient lime-

stone surface which has later been overlain with lime and sandstone to a depth of 40 feet (Fig. 3). Suppose further that the resistivity of the clay is normally much less than one fifth that of the other materials present.

If this filled sink be approximated by a spherical solid, the mean radius may be thought to be about 82.5 feet and the depth to the center about 105 feet. In the set of curves (Fig. 2b), one imagines the curve for which the depth is about 1.27 times the radius and notes that the minimum occurs at an electrode separation about equal to 0.9 times the radius. On the basis of this information alone, it would be concluded that an electrode separation of about 75 feet would be most useful. However, because a traverse will rarely pass directly over the center of the body, the traverse will normally be farther from the center than the 82.5 feet quoted above. Therefore, an optimum electrode separation is probably larger than 75 feet—perhaps as much as 85 or 90 feet.

In deciding on the appropriate spacing between traverses, one concludes that the rule of permissible depth can be generalized to state that, if an anomaly is to be found along a given traverse, the traverse must pass within a distance from the center of the disturbing body roughly equal to the average dimension of the body. In the above example, this means 165 feet. Therefore, in order for the anomaly in the above example to appear on at least two adjacent traverses, a traverse separation of no more than 127.5 feet could be tolerated.

If the disturbing mass actually outcrops, the above discussion must be altered accordingly.

ACKNOWLEDGMENTS

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A METHOD FOR MEASURING THE ELECTRICAL CONDUCTIVITY OF DIAMOND DRILL CORE SPECIMENS*

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ABSTRACT

Conductive methods of measuring electrical conductivity are unsatisfactory for testing diamond drill core specimens of metallic ores. An inductive method which avoids many of the inherent difficulties of the conductive methods is described. The method consists of measuring the change of impedance of solenoid when a core specimen is inserted in it. A correlation between the change of impedance of the solenoid and the physical properties and dimensions of a spherical core is achieved mathematically. This result is extended, empirically, to include cylindrical cores. A convenient way to make the required measurements is outlined, followed by a description of the design of a particular inductive conductivity meter. Sample results obtained with this instrument are presented, and one application of the method is mentioned.

1. INTRODUCTION

Electrical conductivity of a material is commonly measured by obtaining the ratio of current through to voltage across a pair of electrodes fixed to a sample of the material. This procedure is unsatisfactory for diamond drill core specimens of metallic ores which are not reasonably homogeneous. The conductivity so measured may be greatly influenced by contact resistance and by the orientation and distribution of the rock and ore particles. Since drilling is usually perpendicular to the layering of rocks, the conductivity measured in the axial direction of a cylindrical core specimen is greatly influenced by even thin laminations of poorly conducting rock. Further, if contact resistance is to be minimized, the surfaces of the specimen placed in contact with the electrodes must be carefully prepared.

It is the purpose of this note to describe an inductive method of measuring electrical conductivity whereby the aforementioned difficulties are avoided. Instead of measuring the absolute conductivity of the grains of rock, of the grains of metallic ore, or of a mixture of the two, the method discussed below compares the "effective-conductivity" of the specimen with the conductivities of standard homogeneous specimens. The "effective-conductivity" of an inhomogeneous sample is considered herein as equal to the true conductivity of that homogeneous sample of the same size and shape whose response to an applied alternating magnetic field is identical in phase.

The laminations of metallic ore which are oriented perpendicular to the cylinder axis will have maximum response when the magnetic field is parallel to the axis. This condition is secured by inserting the cores in a long solenoid. The response of the core specimen to the field of the solenoid may be determined by

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recording the effect of the core on the current in a secondary winding on the solenoid or, as is done here, by noting the apparent change of impedance of the solenoid when the core is inserted.

II. THEORETICAL BASIS

The following discussion reveals the manner in which the impedance of a solenoid changes with the dimensions and physical properties of the core and with the frequency of the current.

The problem of calculating the change of impedance of a solenoid when a cylindrical core is inserted consists primarily of calculating the response of a conducting circular cylinder to a harmonically varying uniform magnetic field directed parallel to the axis of the cylinder. Admittedly the field inside a solenoid of finite length is not uniform but if the length of the core is of the order of one-half the length of the solenoid, the primary field over the core-region will be nearly uniform. Mathematically, it is not possible to meet the boundary condition that the tangential components of the magnetic field $\overline{H}$ over the total surface of the cylinder be continuous; a discontinuity in $\overline{H}$ arises at the right angle junctions of the cylindrical and end faces. This discontinuity does not arise physically because the junctions are slightly rounded.

It is possible to consider a finite radius of curvature at the junctions of the mathematical model. This procedure, however, leads to very complex expressions which have not been solved explicitly. Some approximation must be made to obtain a useful expression for the impedance of a coil containing a conducting core. Two mathematical solutions for the response of conducting objects in a uniform magnetic field are available which would be of use here; the response of a sphere and of a cylinder of infinite length. To simplify calculations, a spherical core will be considered. This treatment enables the form of the function describing the change of impedance of the solenoid to be obtained. It can be inferred that the nature of the response of the conducting cylinder will be similar to that of the sphere. Empirical data presented later indicates that this is so.

A conducting sphere in a uniform alternating magnetic field behaves as a dipole of moment[1]

$$P_s = -4\pi \frac{H_0 a^3}{2} 3(M + iN) \text{ weber-meters,} \qquad (1)$$

where:

H_0 = incident field in ampere-turns per meter,
a = radius of sphere in meters,

[1] James R. Wait, "A Conducting Sphere in a Time Varying Magnetic Field," *Geophysics*, XVI, No. 4 (1951).

$$M+iN=-\frac{2}{3}\left[\frac{2\mu_1(\sinh\alpha-\alpha\cosh\alpha)+\mu_0(\sinh\alpha-\alpha\cosh\alpha+\alpha^2\sinh\alpha)}{2\mu_1(\sinh\alpha-\alpha\cosh\alpha)-2\mu_0(\sinh\alpha-\alpha\cosh\alpha+\alpha^2\sinh\alpha)}\right],$$

$$\alpha=(i\sigma_1\mu_1\omega-\epsilon_1\mu_1\omega^2)^{1/2}a$$

$$=(i\sigma_1\mu_1\omega)^{1/2}a \text{ (neglecting displacement currents).}$$

σ_1 = conductivity of sphere in mhos per meter;
μ_1 = permeability of sphere in henrys per meter;
ϵ_1 = permittivity of sphere in farads per meter;
ω = angular frequency of source field;
μ_0 = permeability of surrounding medium (air) in henrys per meter.

Thus the phase of the alternating dipole depends on the conductivity, permeability, and radius of the sphere and on the frequency of the applied field H_0.

Another approximation is introduced at this stage in order to express the effect of the sphere on the solenoid in terms of parameters of the solenoid circuit. The secondary field of the sphere may be compared with that of a one turn coil of the same diameter as the sphere. In fact, the sphere is replaced by a one turn coil whose resistance and inductance are such that the induced current in the coil has the same associated magnetic field as the current in the sphere. The resistance and inductance will be functions of the frequency.

Now the electromotive force induced in a one-turn circular coil by a field $H_0e^{-i\omega t}$ in free space is:

$$e=\frac{-\partial\phi}{\partial t}=\frac{-\partial(B\pi a^2)}{\partial t}$$

$$=-\mu_0\pi a^2\frac{\partial(H_0e^{-i\omega t})}{\partial t}$$

$$=\mu_0\pi a^2 i\omega H_0e^{-i\omega t} \text{ volts:} \tag{2}$$

but

$$E=ZI$$

or

$$[R-L\omega i]I=\mu_0\pi a^2 i\omega H_0$$

and

$$I=\frac{\mu_0\pi a^2 H_0\omega i}{R-L\omega i} \text{ amperes.} \tag{3}$$

The dipole moment of a one-turn circular coil is

$$P_c=-\pi a^2 I \text{ weber-meters,} \tag{4}$$

and therefore

$$P_c = -\frac{\pi^2 a^4 \mu_0 H_0 \omega (R + L\omega i) i}{R^2 + L^2\omega^2}. \tag{5}$$

If the sphere and the coil be made equivalent, the moments are identical,

$$P_s = P_c,$$

and

$$-4\pi \frac{H_0 a^3}{2} 3(M + iN) = -\frac{\pi^2 a^4 \mu_0 H_0 \omega (R + L\omega i) i}{R^2 + L^2\omega^2}.$$

Separating the real and imaginary parts of this equation yields

$$4\pi \frac{H_0 a^3}{2} 3N = \frac{\pi^2 a^4 \mu_0 H_0 \omega R}{R^2 + L^2\omega^2}, \tag{6}$$

and

$$4\pi \frac{H_0 a^3}{2} 3M = -\frac{\pi^2 a^4 \mu_0 H_0 \omega^2 L}{R^2 + L^2\omega^2}. \tag{7}$$

From equations (6) and (7) it follows that the equivalent coil resistance R and inductance L are given by

$$R = \frac{\pi a \mu_0 \omega}{6} \cdot \frac{N}{N^2 + M^2} \text{ ohms}, \tag{8}$$

$$L = -\frac{\pi a \mu_0}{6} \frac{M}{N^2 + M^2} \text{ henrys}. \tag{9}$$

The change of impedance of the solenoid due to the presence of the equivalent coil may be found readily once the mutual inductance between the two circuits is determined. Mutual inductance is defined in terms of flux linkage by[2]

$$M_{21} = \frac{\int_s \mu \overline{H}_1 \cdot d\bar{s}_2}{I_1}, \tag{10}$$

where $\int_s \mu \overline{H}_1 \cdot d\bar{s}_2$ is the flux from circuit 1 enclosed by circuit 2 and I_1 is the current in circuit 1. Let $\overline{H}_1$ be the field at the centre of a long solenoid. $\overline{H}_1$ is given by[3]

[2] Ramo and Whinnery, *Fields and Waves in Modern Radio*, John Wiley and Sons Inc. (1944), p. 225.

[3] Harnwell, *Principles of Electricity and Electrogmanetism*, McGraw-Hill (1949), p. 314.

$$\bar{H}_1 = \frac{I_1 \eta' l}{(l^2 + d^2)^{1/2}},$$

and

l = length of the solenoid
d = diameter of the solenoid
η' = turns per unit length of the solenoid.

(For $l \gg d$, the field at the centre is approximately uniform over the cross section of the solenoid.) Hence

$$M_{12} = M_{21} = \frac{\mu_0 H_1 \pi a^2}{I_1},$$

$$M_{12} = \mu_0 \pi a^2 n^1 \frac{l}{(l^2 + d^2)^{1/2}} \text{ henrys.} \tag{11}$$

The solenoid and coil circuits are represented schematically in Figure 1, where the following relations hold:

$$V = (R_1 - i\omega L_1) I_1 + i\omega M_{12} I_2, \tag{12}$$

$$0 = i\omega M_{12} I_1 + (R_2 - i\omega L_2) I_2. \tag{13}$$

From equations (12) and (13) the impedance of the solenoid is obtained, i.e.,

$$Z_1 = \frac{V}{I_1} = R_1 - i\omega L_1 + \frac{\omega^2 M_{12}^2}{R_2 - i\omega L_2}. \tag{14}$$

The quantity

$$\frac{\omega^2 M_{12}^2}{R_2 - i\omega L_2} = \frac{(R_2 + i\omega L_2)\omega^2 M_{12}^2}{R_2^2 + \omega^2 L_2^2}$$

is the change in impedance ΔZ_1 of the solenoid due to the presence of the one-

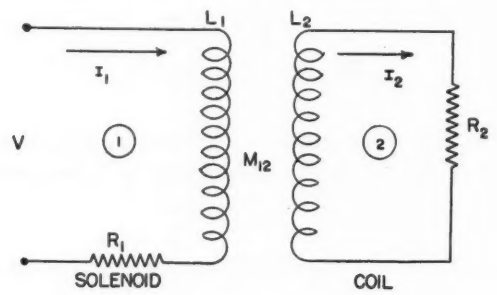

FIG. 1. Schematic representation of the solenoid and coil circuits.

turn coil. The changes in resistance and inductance of the solenoid are found from the relation

$$\Delta Z_1 = \Delta R_1 + i\omega\Delta L_1.$$

Thus

$$\Delta R_1 = \frac{M_{12}^2\omega^2 R_2}{R_2^2 + \omega^2 L_2^2}, \tag{15}$$

and

$$\Delta L_1 = \frac{M_{12}^2\omega^2 L_2}{R_2^2 + \omega^2 L_2^2}. \tag{16}$$

Since the one turn coil is equivalent to a conducting sphere, the change of resistance of the solenoid when the sphere is inserted is found by combining (8), (9), and (11) with (15);

$$\Delta R_1 = 6\mu_0\pi\omega a^3(n')^2 \frac{l^2}{l^2 + d^2} N = K\omega N \text{ ohms.} \tag{17}$$

From (8), (9), (11) and (16) the corresponding change of inductance is

$$\Delta L_1 = -\,6\mu_0\pi a^3(n')^2 \frac{l^2}{l^2 + d^2} M = -\,KM \text{ henrys.} \tag{18}$$

The quantities N and M have been plotted as functions of the dimensionless parameter $\theta = (\sigma_1\ \mu_1\ \omega)^{1/2}\ a$ in Figure 2 for various values of the ratio μ_1/μ_2. μ_1 is the permeability of the core and μ_2 the permeability of the surrounding medium (air). The corresponding response functions for a cylindrical core are of the same form as shown in Figure 3 where empirical data is presented.

Hysteresis occurring in a permeable core has been neglected in the above analysis.

III. MEASURING PROCEDURE

From Figure 2, curve A, it can be seen that the particular phase $\phi = \tan^{-1}(N/M) = \pi/4$ of the response of the sphere may be obtained with a sphere of radius a, conductivity σ, at a frequency ω or with a sphere of radius a, conductivity $\eta\sigma$ at a frequency ω/η where η may take any value. The same consideration may be expected to apply to cylinders of identical length, as the empirical data of Figure 3 indicate. Thus when a specimen is inserted in the solenoid, the frequency is varied until $N = M$ or until the standard phase

$$\phi = \tan^{-1}\frac{N}{M} = \tan^{-1}\left(\frac{-\,\Delta R_1}{\omega\Delta L_1}\right) = \pi/4$$

is obtained. The frequency at which this occurs is noted and the conductivity cor-

responding to this frequency, for a given core length, radius, and permeability is then read from a calibration chart.

One convenient method of measuring the phase of the response involves connecting the solenoid in series with a variable condenser and an oscillator. At resonance, the Q of the circuit is given by

$$Q = \frac{\omega L}{R} = \frac{1}{\omega C R}.$$

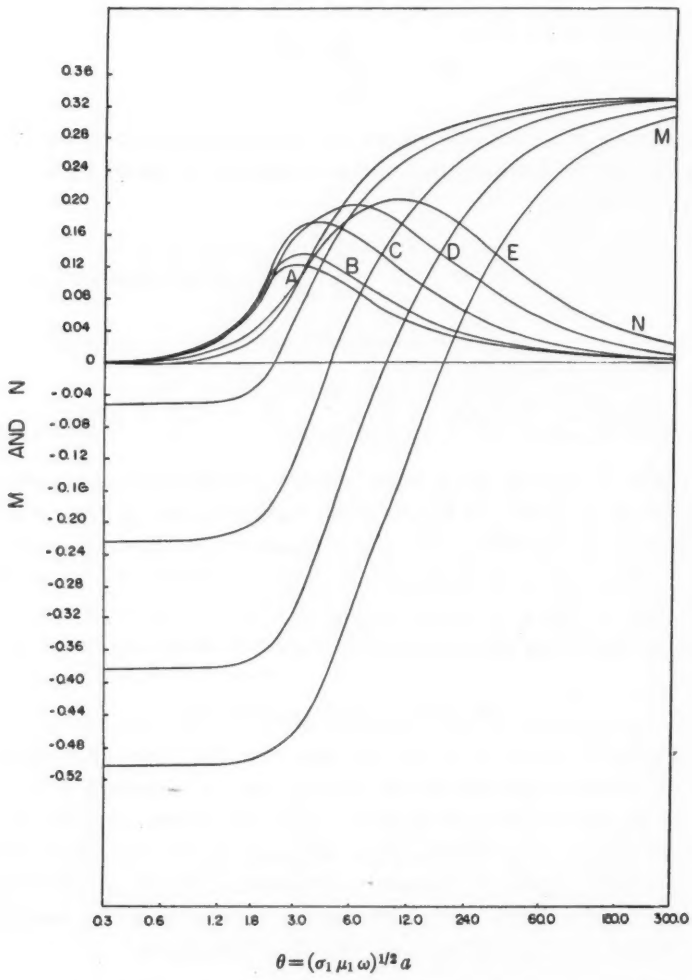

FIG. 2. *Response of Sphere.*—In-phase component M and out-of-phase component N versus dimensionless parameter θ for various values of permeability contrast.

Curves	A	B	C	D	E
μ_1/μ_2	1.0	1.25	2.5	5.0	10.0

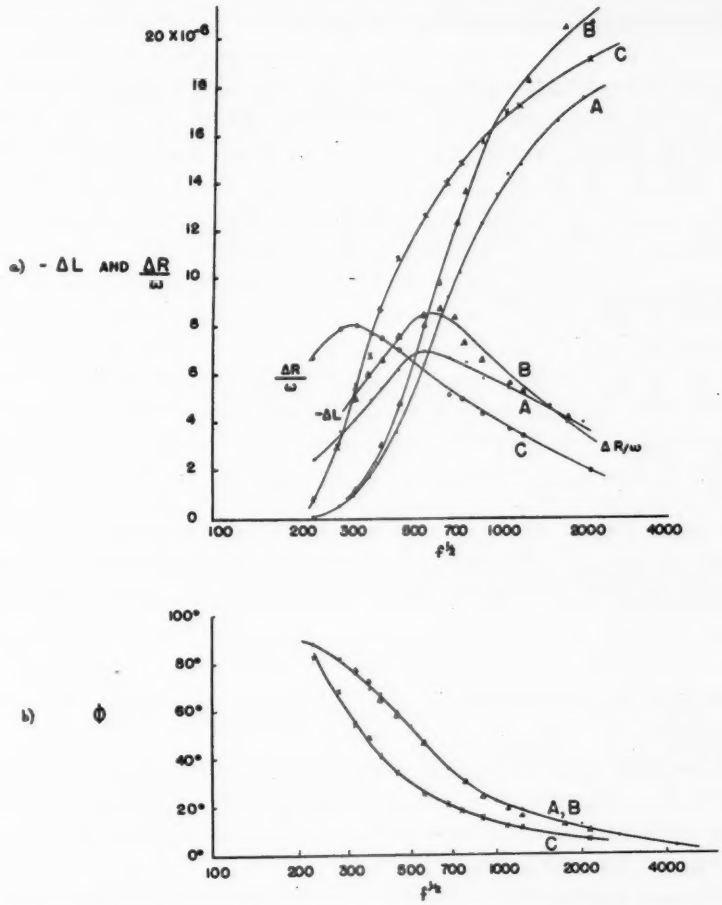

FIG. 3. Change of solenoid inductance and resistance versus frequency for several cores.

A. Carbon Core: length $=2\frac{1}{2}''$, radius $=\frac{7}{16}''$, $\sigma=2.9\times10^{4}$ mhos/meter, $\mu=\mu_0=4\pi\times10^{-7}$ henrys per meter.

B. Carbon Core: length $=4\frac{1}{2}''$, radius $=\frac{7}{16}''$, $\sigma=2.9\times10^{4}$ mhos/meter, $\mu=\mu_0=4\pi\times10^{-7}$ henrys per meter.

C. Pyrrhotite Core: length $=2\frac{1}{2}''$, radius $=\frac{7}{16}''$, $\sigma=4.3\times10^{4}$ mhos/meter, $\mu=1.23\times4\pi\times10^{-7}$ henrys per meter.

Let the Q of the circuit with no core in the solenoid be

$$Q_1=\frac{\omega L_1}{R_1}=\frac{1}{\omega C_1 R_1}. \tag{19}$$

Insertion of the core alters both R and L, necessitating a change in C to maintain resonance at the same frequency. Then with the core inserted

$$Q_2=\frac{\omega L_2}{R_2}=\frac{1}{\omega C_2 R_2}. \tag{20}$$

From (19) and (20) there results

$$\Delta R = R_2 - R_1 = \frac{1}{\omega}\left(\frac{1}{Q_2C_2} - \frac{1}{Q_1C_1}\right) \text{ ohms}, \tag{21}$$

and

$$\Delta L = L_2 - L_1 = \frac{1}{\omega^2}\left(\frac{1}{C_2} - \frac{1}{C_1}\right) \text{ henrys}. \tag{22}$$

Combining (21) and (22) yields

$$\frac{-\Delta R}{\omega \Delta L} = \left(\frac{\dfrac{1}{Q_1C_1} - \dfrac{1}{Q_2C_2}}{\dfrac{1}{C_2} - \dfrac{1}{C_1}}\right). \tag{23}$$

The four quantities C_1, C_2, Q_1, Q_2 are measured and the phase calculated. Thus it is necessary to determine the phase ϕ corresponding to several frequencies and interpolate graphically to obtain the frequency corresponding to $\phi = \pi/4$.

IV. INSTRUMENTATION

The design of the inductive conductivity meter was based on the following considerations:

1. The device must be capable of measuring a wide range of conductivities. The electrical conductivities of metallic sulphide ores vary from 10^{-2} to 10^{5} mhos per meter while the conductivities of most of the massive ores lie in the narrower range 10^{2} to 10^{5} mhos per meter.

2. Accuracy greater than 10 percent in any one measurement is not required since the device is intended to be used to correlate the results of an electromagnetic survey with electrically conducting portions of a drill core section, and since the conductivity may vary widely in even short distances through an orebody.

3. Simplicity of design and operation and the utilization of available metering equipment are essential to minimize the cost of this essentially auxiliary device.

4. Measurement will be at a phase which corresponds to a relatively high amplitude response (see Fig. 3). Moderate accuracy is thus readily attained, and variation of accuracy with amplitude does not require attention. The rate of change of phase with frequency is a maximum at $\phi = \pi/4$.

5. The oscillator connected in series with the solenoid and the variable condenser should be capable of producing useful signals over a range of at least three decades in frequency.

6. Preliminary measurements on typical core samples showed that the standard phase of $\pi/4$ resulted when the product $\sigma\mu\omega$ had the approximate value 8.9×10^{4}. If the permeability of the sphere is taken as that of free space, the fre-

quency $f=\omega/2\pi$ required is 100 Mc/sec for $\sigma=10^2$ mhos per meter and 100 Kc/sec for $\sigma=10^5$ mhos per meter.

The Boonton Radio Corporation Q-meter type 160A is well suited to serve both as the oscillator and as the indicating device in accordance with the above requirements and consequently was used to make the measurements cited here. The frequency range of the instrument is 50 Kc/sec to 75 Mc/sec. Circuit Q's between 20 and 250 may be measured to the nearest half digit. The internal variable condenser ranges from 30 to 460 $\mu\mu$ farads and provision is made for connecting external condensers in parallel with it. Changes in the capacity required to resonate a coil may be measured to the nearest 0.01 $\mu\mu$ farad.

The design of suitable solenoids or coils remains to be considered. Here a process of trial and error proves most satisfactory. Since the Q of the coil may be measured only to the nearest half digit on the Q-meter, coils of fairly high Q are required in order to obtain reasonable accuracy when measuring ΔR [see equation (21)]. To maintain a high Q over the three decade frequency range, it was found necessary to design four coils. The dimensions and characteristics of these coils are given in Table I.

In section II above, the capacity between the core sample and the solenoid was neglected. This capacity may be estimated since the core and the coil constitute, effectively, a cylindrical condenser. The capacity of a cylindrical condenser is given by[4]

$$C = \frac{1.41}{ln\ b/a}\ \mu\mu \text{ farads/in},$$

where

b = the radius of the coil

and

a = the radius of the core.

TABLE I

Coil	Turns	Wire Size	Inductance	Q	Diam.	Length	Frequency Range
1	440	#30	0.0230 h	50–100	2″	4.4″	20 to 150 Kc
2	91	#20	0.263 mh	70–150	2″	3.8″	100 Kc to 1.5 Mc
3	27	#15	0.0245mh	100–200	2″	3.7″	600 Kc to 4.5 Mc
4	5	#12	1.37 h	100–180	2″	2.6″	4.0 Mc to 20.0 Mc
0*	5,000	#24	0.940 h	30– 60	2″	4.5″	500–20,000 cps.

* A special coil used only for general calibration with brass cylinder.

Note: No. 1 coil was universally wound in 11 π's in order to reduce distributed capacities. Coils No. 2, No. 3, and No. 4 were single layer coils. Coil 0 consisted of 25 layers of approximately 200 turns each.

[4] Christie, *Electrical Engineering*, McGraw-Hill (1938), p. 19.

Assuming a cylindrical core of the same length as the coil, the value of this capacity is found, for example, to be 5.11 $\mu\mu$ farads for coil No. 2. Such a capacity increases the distributed capacity of the coil as is illustrated in Figure 4a. The circuit of Figure 4a may be replaced by that of Figure 4b where C_C has a maximum value of 5.11 $\mu\mu$ farads but a probable value considerably lower. It is suggested[5] that $C_D = \frac{1}{3}Cl$ where C is the distributed capacity per unit length and l is the length. The capacities C_C and C_D are then in parallel with the coil and affect the impedance appearing across the coil terminals. C_D is fixed in the circuit but C_C only occurs when the core is inserted. Thus the change of impedance across the

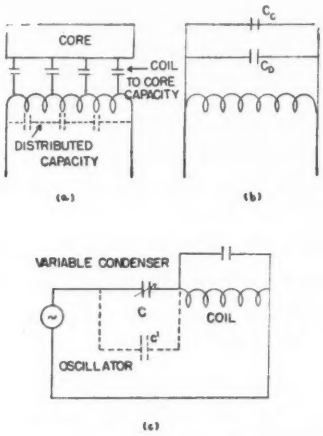

FIG. 4. Equivalent circuits of core tester showing the effect of distributed and coil to core capacities.

terminals of the coil is affected by C_C as well as by the eddy currents in the core. This gives rise to an error in the quantities N and M of equations (17) and (18). The error is not large, however, provided $X_c = (1/\omega C_c) \gg X_L = \omega L$. In effect C_c places an upper limit to which any coil may be used satisfactorily. To extend the useful range of each coil, an electrostatic shield was inserted between the coil and the core. This shield consisted of many pieces of copper wire cemented lengthwise along a cylindrical tube of bakelite. At one end these wires were connected electrically, but were otherwise separated. The common end was connected to the "ground" terminal of the Q-meter. The wires were oriented parallel to the magnetic field in an attempt to minimize eddy currents in the field. Despite this precaution, the presence of the shield altered the effective impedance of each coil. However, this effect is unimportant since the shield is in the coil at all times.

The distributed capacity C_D and other stray impedances cause the coil in-

[5] J. V. Scott, M.A. Thesis, Physics Dept. University of Toronto, 1951. "Characteristic Impedance and Pulse Shape in Delay Lines."

ductance, as calculated from the formula $L=1/\omega^2 C$ where C is the tuning capacity of Figure 4c, to increase with frequency. However L tends asymptotically towards its true value (recorded for all coils in Table I) as the frequency decreases. At any one frequency, these stray impedances may be considered as an error in measurement of C. This error C' may be calculated from the true and apparent inductance values and added to C.

V. CALIBRATION

The operating principle has been outlined in section III above. The actual measurement of effective conductivity can be made quite readily once the device has been calibrated with standard homogeneous cylinders. For spherical cores, calibration should consist of finding the value of $\theta=(\sigma\mu\omega)^{1/2}\,a$ at $\phi=\pi/4$ for known values of σ, μ, ω, and a. (The required value of θ is known to be 3.45 for $\mu=4\pi\times 10^{-7}$: see Figure 2.) If a and μ are constant, this amounts to determining the frequency, for several known values of σ, at which the product $\sigma\mu\omega$ has the value corresponding to the phase $\phi=\pi/4$. For a cylindrical core, by analogy, this latter procedure appears to be appropriate when the permeability, radius and length of the core are constant. To ensure that it is appropriate, the value of the product $\sigma\mu\omega$ should be determined for several values of the three variables and for several core lengths.

It is difficult to obtain homogeneous standard specimens whose conductivities completely span the 10^2 to 10^5 mhos per meter range of conductivities suggested for massive sulphide ores. Five cylinders with conductivities in the range 10^4 to 10^7 mhos per meter were used for calibrating purposes here. These cylinders were of brass, mercury, gas carbon, carbon, and graphite, each with a diameter of $\frac{7}{8}$ inch and a length of $4\frac{1}{2}$ inches. Cores cut with an EX type diamond drill have this diameter. If $P_{\pi/4}$ is the value of the product $\sigma\mu\omega$ for $\phi=\pi/4$, then $P_{\pi/4}$ should be a constant, according to Figure 2, for any combination of the factors σ and ω at constant μ. That is, the relation between σ and $f=\omega/2\pi$ is linear. This linearity is illustrated by the empirical data of Figure 5 which constitutes the calibration chart for the conductivity meter described above. The "effective conductivity" of an inhomogeneous cylindrical core of $\frac{7}{8}$ inch diameter and permeability $\mu=\mu_0=4\pi\times 10^{-7}$ is then given by

$$\sigma=\frac{P_{\pi/4}}{\mu_0\omega}=\frac{11\times 10^9}{f_{\pi/4}}.$$

For the cylinders used in calibration, μ was assumed equal to $\mu_0=4\pi\times 10^{-7}$ henrys per meter. For comparison, a sample of pyrrhotite ($\sigma=4.3\times 10^4$ mhos per meter; $\mu=1.23\times 4\pi\times 10^{-7}$ henrys per meter) was used to calibrate the meter. A different value of $P_{\pi/4}$ resulted, as might have been predicted by analogy with the theory of a spherical core (see Fig. 3). Note that the order of magnitude of the conductivity of a pyrrhotite specimen may be obtained even when the permeability is ignored.

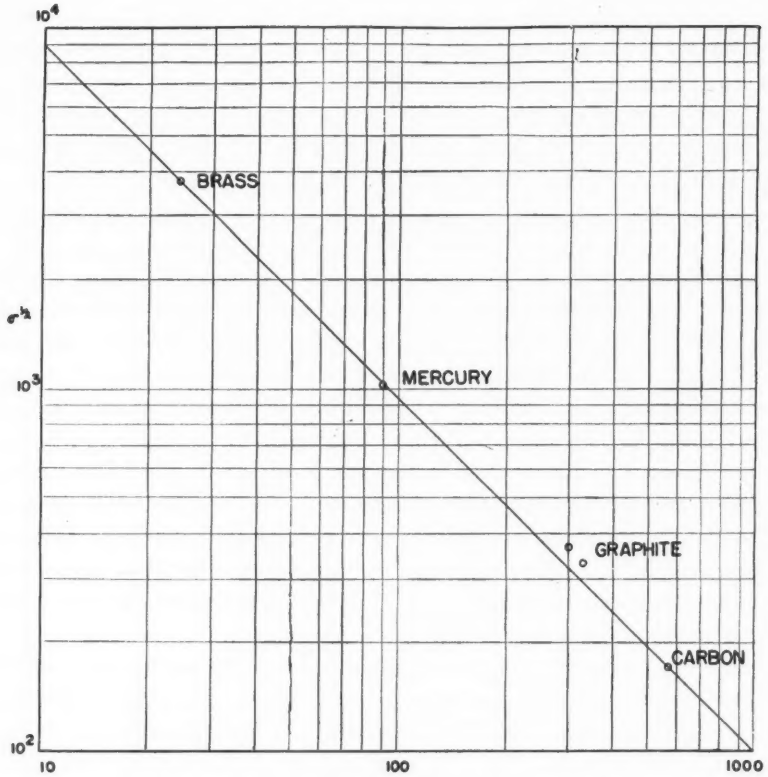

FIG. 5. Calibration chart showing linear relation between conductivity of core and frequency at which phase of response of core is standard $\pi/4$.

$$\sigma = \frac{11 \times 10^9}{f_{\pi/4}}$$

For a cylindrical core, the amplitude depends on both the length and the radius of the cylinder. The variation of amplitude with length may be seen in Figure 3. One very important conclusion may be drawn from curves A and B of Figure 3: there is no perceptible variation of phase with length of cylinder within the limits $2\frac{1}{2}'' < l < 4\frac{1}{2}''$. Thus it is not necessary to cut diamond drill core specimens to a precise standard length in order to obtain a measure of their effective conductivities.

When using the brass and mercury cylinders in the calibration, it was neces-

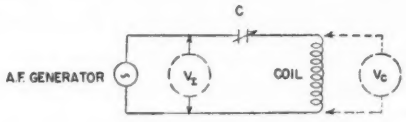

FIG. 6. Circuit employed when calibrating with brass and mercury cylinders.

sary to replace the Q-meter by an a.f. generator and a vacuum tube voltmeter since $f_{\pi/4}$ was well outside the range of the Q-meter. In this instance, the Q of the coil was found from the relation V_1/V_c where the quantities are as shown in Figure 6.

VI. CONCLUSION

The inductive conductivity meter has so far proven to be of value in obtaining a measure of the "effective conductivity" of inhomogeneous samples of diamond drill cores. Possibly its chief application will be as a correlative tool used in conjunction with inductive electromagnetic surveys. In such an application, true conductivities of the ore and rock media are not required but instead a quantitative estimate of the effect of the various portions of an orebody on an applied electromagnetic field is needed.

The possibility of using one inductive device to measure both permeability and conductivity of core samples is evident after a study of Figure 2.

ACKNOWLEDGMENTS

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CONTRIBUTION TO THE METHOD OF TORSION BALANCE SURVEYING IN UNDERGROUND*

ŽELJKO ZAGORAC†

ABSTRACT

A manner of interpretation of torsion balance survey in underground is shown, when the gradients Uxz, Uyz, and the curvature value Uxy are measured. Values Uxy and Uxz are composed as vectors in the vertical plane Z-Y; Uyz and Uxy are composed in the plane Z-X. On various examples it is shown that the resulting vectors give a better means of determining the position of ore bodies. An example of actual torsion balance survey in an iron ore mine is given. The method of eliminating the influence of mass irregularities close to the instrument by means of parallel profiles is described and discussed.

Torsion balance work in underground has certain advantages in comparison with the work on the surface. The influence of topography is less because of greater distance and can be calculated very quickly from maps by means of suitable diagrams. This gives a possibility for exploration in areas of rough terrain—such as the chromite, iron, and many other mining districts in Yugoslavia—where work on surface has practically no value.

The influence of the hollow space of the gallery in which the survey is made is quite small for gradients, but for the curvature value $U_\Delta = Uyy - Uxx$ it is very great.‡ This value often cannot be determined with sufficient accuracy, and so the resulting curvature value $R = (U_\Delta{}^2 + 4Uxy^2)^{1/2}$ can also not be calculated accurately. This is the reason why some authors recommend measuring only gradients in underground.§ But the influence of the gallery hollow space on the value Uxy is not great, and it may be said that this value without the other curvature value U_Δ can be very useful in geological interpretation.

Accordingly, if for the o-azimuth (the $+X$ axis) the direction of the gallery is chosen, measurements are made in four azimuths: 0°, 90°, 180°, 270°, and values Uxz, Uxy, and Uyz are calculated using the generally known formulas. Now, in the same manner as the gradients Uxz and Uyz are vectorially composed in the horizontal plane X-Y, we can also draw, in the vertical plane Y-Z, the value Uxz in the direction Z, the value Uxy in the direction Y; then the resulting vector gives the highest increase of the gravity component X in the plane Y-Z (Figs. 1c–4c).

Also in the plane X-Z we can draw the Uyz gradient in the direction Z and the Uxy value in the direction X, then the resulting vector will give the highest increase of the gravity component Y in the plane X-Z (Fig. 1d–3d).

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‡ O. Meisser und F. Wolf, "Geophysikalische Messungen unter Tage," *Zeitschrift für Geophysik* 6 (1930), 13–21.

§ H. Haalck, *Lehrbuch der angewandten Geophysik* (1934), 86–88.

Figures 1–3 represent such vectors for various positions of ore bodies of spherical and cylindrical shapes. The difference of the density of ore and of the surrounding stone is $\Delta\sigma=\sigma-\sigma_0=2.0$ gr/cm³. In all figures a) is an acsonometric drawing with the position of the ore body and of the gallery, b) is the plane *X-Y*, c) the plane *Y-Z*, and d) the plane *X-Z*.

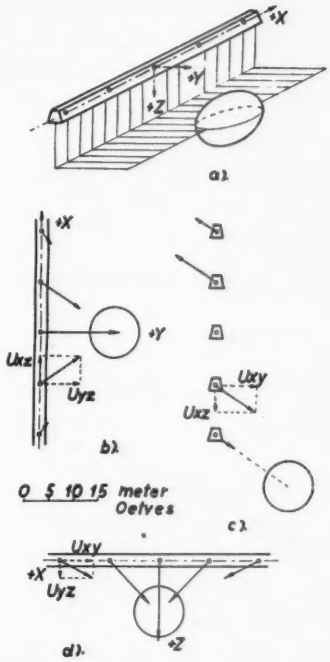

FIG. 1. Gradients of various gravity components for a sphere.

It is obvious that the vectors with *Uxy* give a much clearer image about the position of ore bodies than horizontal gradients alone. For spheres, resulting vectors in all three planes give the direction to the ore. In Figure 3, this is only at c). In the case where the ore is on the level of the instrument (Fig. 2), there are no gradients *Uxz* and *Uyz*, but the value *Uxy* gives the direction to the ore. In cases of ore bodies of irregular shape the image becomes more complicated, but the practical utility of the value *Uxy* can also be shown.

As an example, following are the results of a survey in the iron ore mine Vareš in Yugoslavia. The results are shown in Figure 4. The surveying has been done by the institution "Geozavod" under the direction of Professor Baturić from the University Zagreb. At the time of the survey (1947) only gradients *Uxz* and *Uyz* were used. The instrument employed was an Askania Torsion Balance S 20.

In Figure 4 in a) the vectors $Gz=(Uxz^2+Uyz^2)^{1/2}$ are drawn in the plane *X-Y*, in b) the drawing plane is *Y-Z*, and vectors $Gx=(Uxz^2+Uxy^2)^{1/2}$ are shown, in c) the drawing plane is *X-Z*, and $Gy=(Uyz^2+Uxy^2)^{1/2}$ are shown.

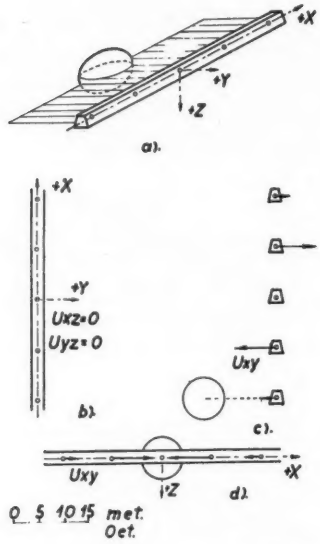

FIG. 2. Gradients of various gravity components for a sphere on the level of the instrument.

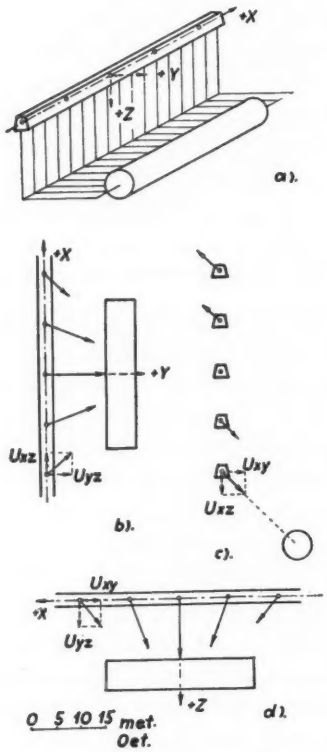

FIG. 3. Gradients of various gravity components for a cylinder.

Stations 5–9 give a similar picture as in the theoretical example in Figure 3. The vectors in Figure 4c are diverging because the ore body is south below the gallery (in the direction $-Y$ and $+Z$). If the Figure 4c were to be drawn sighting from behind, the gradients would be converging to the ore body.

It can be concluded that the ore body which caused the anomaly is of oblong shape, and that the axis of this body is south below the gallery under the angle of 60° from the horizon (from Fig. 4b). In station 7 this angle is smaller, but this can be attributed to the irregular shape of the body. Accordingly, the exploratory bore hole must be made at station 7 to the south under the angle of 60° from the

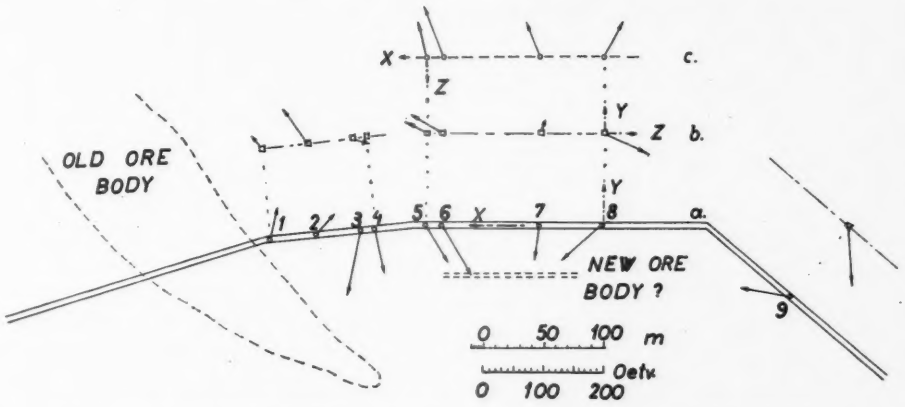

FIG. 4. Results of torsion balance exploration in the iron ore mine Vareš in Yugoslavia.

horizon downwards. With the results of such a bore hole more detailed interpretation could be made. But unfortunately, after the geophysical exploration, no more work has been done in this place. The approximate position of the axis of the "New Ore Body," drawn with double dotted lines in Figure 4 is determined only from torsion balance surveying. Perhaps this ore body could be connected with the "Old Ore Body" drawn in Figure 4 with dotted lines, which was known before the torsion balance survey was made.

The results of measurements and corrections are given in Table I. The following explanation applies to the headings of columns.

Normal correction: Correction for the normal gradient directed toward the North in the Northern Hemisphere.

Gallery correction 1: Correction for the influence of small mass irregularities close to the instrument.

Gallery correction 2: Correction for the influence of the changed direction of the gallery near the station.

Surface correction: Correction for the influence of the surface topography, taken from 50 m to 7.5 km horizontal distance of each station.

As it can be seen from the Table I, the influence of the surface topography on

TABLE I
RESULTS OF TORSION BALANCE SURVEYING IN THE IRON ORE MINE VAREŠ IN YUGOSLAVIA

Station		Measured Value	Normal Correction	Gallery Corr. 1	Gallery Corr. 2	Surface Corr.	Summary Corrections	Final Value
1	*Uxy*	− 16.8	+0.3	+30.5	−2.8	+ 12.4	+ 40.4	+23.6
	Uxz	+200.5	+0.5	− 4.9	0.0	−212.5	−216.9	−16.4
	Uyz	+125.0	−8.2	+ 5.1	0.0	− 70.9	− 74.0	+51.0
2	*Uxy*	+ 51.2	+0.3	0.0	0.0	+ 9.2	+ 9.5	+60.7
	Uxz	+184.3	+0.5	0.0	0.0	−219.1	−218.6	−34.3
	Uyz	+147.2	−8.2	−44.8	0.0	− 60.7	−113.7	+33.5
3	*Uxy*	− 17.5	+0.3	0.0	0.0	+ 5.4	+ 5.7	−11.5
	Uxz	+255.7	+0.5	0.0	0.0	−225.4	−224.9	+30.8
	Uyz	− 0.7	−8.2	−45.1	0.0	− 49.3	−102.6	−103.3
4	*Uxy*	− 15.3	+0.3	0.0	0.0	+ 4.6	+ 4.9	−10.4
	Uxz	+219.0	+0.5	0.0	0.0	−227.8	−227.3	− 8.3
	Uyz	+ 28.5	−8.2	−48.4	0.0	− 47.2	−103.8	−75.3
5	*Uxy*	+ 13.5	−0.2	0.0	−0.4	+ 6.6	+ 6.0	+19.5
	Uxz	+188.2	−0.2	0.0	0.0	−224.9	−225.1	−36.9
	Uyz	+ 12.3	−8.2	−48.5	0.0	− 16.2	− 72.9	−60.6
6	*Uxy*	+ 23.1	−0.2	0.0	0.0	+ 9.0	+ 8.8	+31.9
	Uxz	+171.4	−0.2	0.0	0.0	−221.8	−222.0	−50.6
	Uyz	− 27.7	−8.2	−33.4	0.0	− 14.6	− 56.2	−83.9
7	*Uxy*	+ 17.7	−0.2	0.0	0.0	+ 5.8	+ 5.6	+23.3
	Uxz	+197.5	−0.2	0.0	0.0	−190.3	−190.5	+ 7.0
	Uyz	− 28.6	−8.2	−21.7	0.0	+ 1.0	− 28.9	−57.5
8	*Uxy*	− 35.9	−0.2	−16.2	0.0	+ 18.5	+ 2.1	−33.8
	Uxz	+243.2	−0.2	+ 1.5	0.0	−175.2	−173.9	+69.3
	Uyz	− 17.9	−8.2	−53.7	0.0	+ 21.7	− 40.2	−58.1
9	*Uxy*	− 44.9	−2.7	−41.6	0.0	+ 14.8	− 29.5	−74.4
	Uxz	+142.4	−5.3	− 5.9	0.0	− 60.7	− 71.9	+70.5
	Uyz	− 12.0	−6.0	−94.0	0.0	+ 72.0	− 28.0	−40.0

gradients is very great, and on the curvature value *Uxy* quite small. This correction has been calculated by means of the usual standard diagrams for interpretation and topographic correction in surface work. For one part of the terrain the maps of scale 1:2,500 have been used, but for the other part only maps of scale 1:50,000 were available. This resulted in reduced accuracy of corrections.

The underground correction of 0.0 Oetvos for *Uxz* and *Uxy* used on some stations is the result of the gallery being built in concrete at these places. At these stations empty space of unknown size between the wall and the concrete also reduced the accuracy of results.

In 1947, when this exploration was made, corrections for the influence of the mass irregularities close to the instrument were calculated only for the value *Uyz*. This has been made by using the method established by Prof. Baturić from the University of Zagreb (not published). Later I worked out a similar method

for the corrections of values *Uxy* and *Uxz*. The methods for all the three corrections are as follows (Fig. 5):

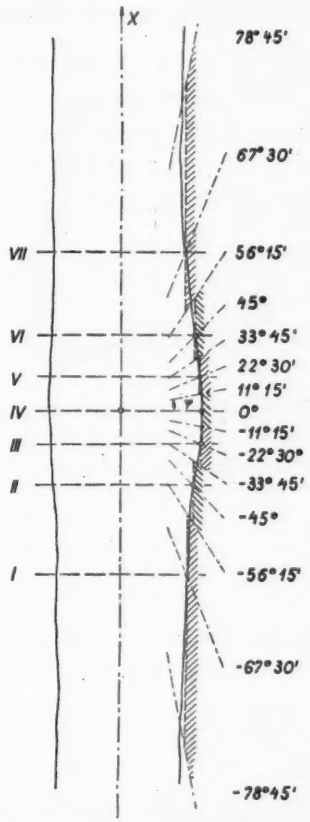

FIG. 5. Arrangement of parallel profiles in the galléry.

From the station *O* directions making an angle of 0°, ±22.5°, ±45°, and ±67.5° with the *Y* axis are fixed. On the places where these directions are touching the wall, parallel profiles I to VII perpendicular to the *X* axis are measured. Now it is considered that every mass irregularity measured on each profile is extended in a direction parallel to the *X* axis within the limits Ψ_1 to Ψ_2 as shown in Figure 5 and Table II.

As it is evident that the masses on the left and on the right side of each profile influence the *Uyz* value in opposite signs, the left side of a profile is drawn rotated to the right side and the difference (crossed surface in Fig. 6) is taken in account.

This surface is laid onto K. Jung's diagram for two-dimensional bodies* (Fig.

* Reich und Zwerger: *Taschenbuch der angewandten Geophysik* (1943), Tafel 6.

7), and the covered fields are numbered. If the masses were extending in the X direction from $-\infty$ to $+\infty$, the number of fields, multiplied by 0.667 σ (σ is the density) would give the effect on Uyz in Oetvos units. As the extending of the masses is considered to be in the higher mentioned limits (Ψ_1 to Ψ_2), this number

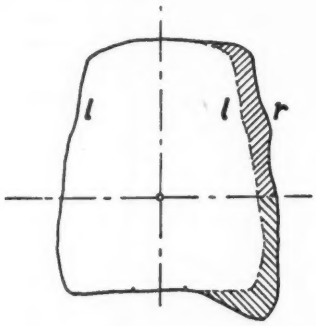

FIG. 6. A profile for correcting Uyz.

has also to be multiplied by a coefficient C, derived in the following way:

From the formula:

$$Uyz = 3K\sigma \iiint \frac{YZdxdydz}{r^5}$$

taking the extension only in the direction X, and introducing $X=\rho \cdot tg\psi$, $r=\rho/\cos\psi$, $dy \cdot dz = dP$, $Z=\rho \sin\phi$, $Y=\rho\cos\phi$ (Fig. 8), and integrating from X_1 to X_2 or

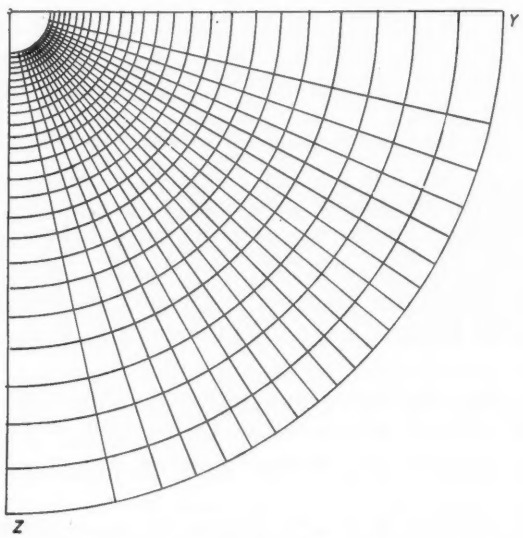

FIG. 7. K. Jung's diagram used here for underground correction of Uyz. 1 Field=0.667 σ Oetvos.

from ψ_1 to ψ_2 we derive

$$Uyz = \frac{3K\sigma dP \sin\phi \cos\phi}{\rho^2} [\sin\psi_2 - \sin\psi_1 - (\sin^3\psi_2 - \sin^3\psi_1)].$$

For a mass unlimited in the direction X, $\psi_1 = -90°$, $\psi_2 = +90°$ and

$$Uyz = \frac{3}{\rho^2} K\sigma dP \sin\phi \cos\phi \cdot \frac{4}{3}.$$

So, the coefficient, with which the number of fields in Jung's diagram is to be multiplied, is:

$$C = \tfrac{3}{4}[\sin\psi_2 - \sin\psi_1 - \tfrac{1}{3}(\sin^3\psi_2 - \sin^3\psi_1)].$$

From that formula we can calculate the coefficients C as shown in Table II.

TABLE II

COEFFICIENTS FOR THE CORRECTION OF Uyz

Profile	ψ	ψ_1	ψ_2	C
I	−67.5	−78.75	−56.25	0.020
II	−45	−56.25	−33.75	0.106
III	−22.5	−33.75	−11.25	0.229
IV	0	−11.25	+11.25	0.290
V	+22.5	+11.25	+33.75	0.229
VI	+45	+33.75	+56.25	0.106
VII	+67.5	+56.25	+78.75	0.020

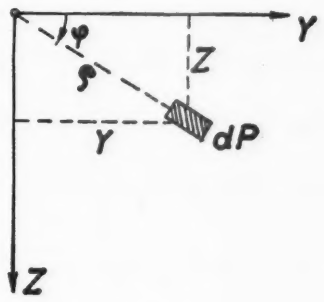

FIG. 8

For the value Uxy and Uxz a similar method is applied, but another diagram is constructed:

We begin with the formula:

$$Uxy = 3K\sigma \int\int\int \frac{\rho^2 x \cos\phi}{(\rho^2 + x^2)^{5/2}} d\rho dx d\phi \text{ (Fig. 8).} \qquad (1)$$

Integrating X from 0 to ∞, ρ from ρ_1 to ρ_2, and ϕ from ϕ_1 to ϕ_2, we derive:

$$Uxy = K\sigma(\sin \phi_2 - \sin \phi_1)(\log \text{nat } \rho_2 - \log \text{nat } \rho_1).$$

This formula is used for constructing the diagram of Figure 9.

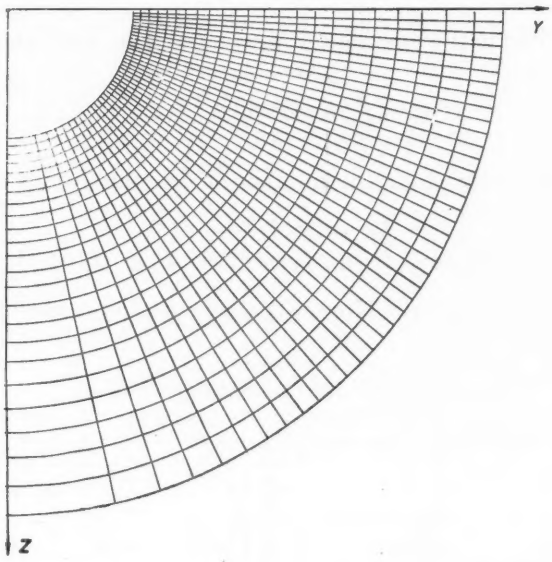

FIG. 9. Diagram for correcting Uxy. 1 field = 0.1 σ Oetvos. (For Uxz Y and Z axes change places.)

The values $\phi_1, \phi_2, \rho_1, \rho_2$ are chosen so that the value of each field in the diagram is 0.1 σ Oetvos when the extending of the mass in the X axis direction is from 0 to ∞.

We derive the coefficients for the profiles I–VII in a similar manner as for Uyz:

For one field of the diagram we receive from (1)

$$Uxy = K\sigma \cos \phi dP \frac{1}{\rho^2} (\cos^3 \psi_1 - \cos^3 \psi_2).$$

For $X_1 = 0$, $X_2 = \infty$, or $\psi_1 = 0°$, $\psi_2 = 90°$ we receive:

$$Uxy = K\sigma \cos \phi dP \frac{1}{\rho^2},$$

so the coefficient C for Uxy is

$$C = (\cos^3 \psi_1 - \cos^3 \psi_2).$$

This gives Table III.

TABLE III

COEFFICIENTS FOR CORRECTION OF *Uxy* AND *Uxz*

Profile	*C*
I	0.164
II	0.403
III	0.369
IV	0.000
V	0.369
VI	0.403
VII	0.164

Angles ψ, ψ_1, and ψ_2 are the same as in Table II.

For *Uxz* the same coefficients and the same diagram as for *Uxy* are to be used, only the axes *X* and *Z* change their places. For *Uxz* the surface to be used with the diagram is not the difference between the right and the left side of the same profile, as for *Uyz*, but the difference between profile I and VII, II and VI, III and V. For *Uxy* the one as well as the other difference can be used.

If needed, more than 7 profiles could be used. The integration would then be made in corresponding limits.

The method of parallel profiles has many advantages compared with the

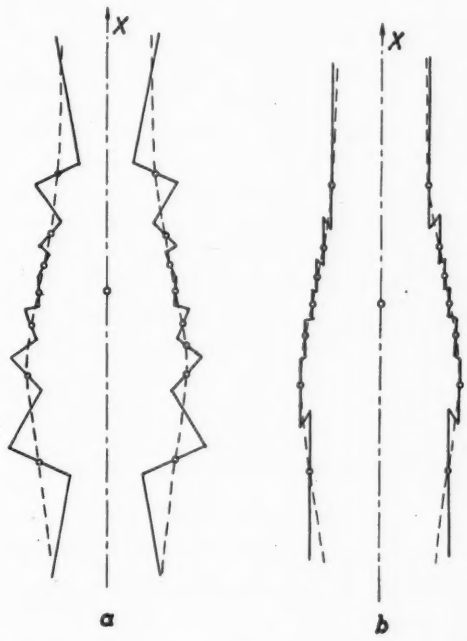

FIG. 10. An enlarging of the gallery shown a) in radial profiles, b) in the parallel profile method.

method of radial profiles. The assumption of the extension of mass irregularities in the direction of the gallery is nearer to the truth then the assumption they extend symmetrically on both sides of a radial profile. This can be shown in Figure 10.

So, to receive the same accuracy of correction, more radial than parallel profiles are needed. The measurement of parallel profiles takes also lesser time. In the example shown in this article profiles have been measured with horizontal and vertical stabs with etched centimeters. When a greater number of stations is to be occupied, it will pay to build out a device for faster measuring or for automatic drawing of profiles.

The method of using the Uxy value for determining the direction to the geological body which caused the anomaly can naturally be used also in surface measurements. But, on the surface, the torsion balance can not compete with the gravimeter, which can readily cover a large area and give a clearer picture of the position of the ore then in underground, where the measurement is possible only in one or few galleries. So the presence of one value more (Uxy) is needed more in underground work than on the surface.

ACKNOWLEDGMENT

I wish to express my deep indebtedness to Prof. Baturić of the University Zagreb for permission to use in this article the results of his work mentioned in the text.

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2, 613, 247. F. W. Lee. Iss. 10/7/52. App. 3/19/48.

Method of Geophysical Prospecting. A method of delineating an electrically-polarizable body penetrated by a borehole by passing a current between electrodes equidistant and on line with the hole, and measuring the potential between an electrode in the hole and surface electrodes, intermediate the hole and the current electrodes, and repeating the test at various azimuths.

U. S. No. 2,613,250. H. L. Bilhartz and H. F. Dunlap. Iss. 10/7/52. App. 10/6/50. Assign. The Atlantic Refining Co.

Method for Measuring Resistivity of Earth Samples. A method of measuring the electrical resistivity of a core sample by passing a current through it from end to end and measuring the potential drop between a number of points along its length, measurements being taken at different saturation values during a capillary-pressure test.

U. S. No. 2,619,520. C. R. Nichols. Iss. 11/25/52. App. 3/2/49.

Electrical Prospecting. A d-c electrical prospecting method in which the measured potentials are integrated during an observation period of about five minutes or more in order to minimize the effect of stray earth currents.

U. S. No. 2,623,097. G. Kunetz. Iss. 12/23/52. App. 5/20/47 and 5/20/48. Assign. Compagnie Generale de Geophysique.

Method for the Electric Prospection of the Subsoil. An electric earth investigating system in which the field of telluric currents is recorded at points over the area being investigated and the ellipse representing the locus of the field vector is drawn for each point.

U. S. No. 2,623,916. W. C. Welz. Iss. 12/30/52. App. 6/24/48. Assign. Schlumberger Well Surveying Corp.

Electrical Measuring System. An indicating system for comparing voltages in electrical prospecting and in which the voltages are fed into two arms of a wye-connected network whose ends are connected to the apexes of a delta-connected circuit so that meters in the other four branches respectively give the values of the voltages and their sum and their difference.

U. S. No. 2,623,924. W. O. Cartier, G. H. McLaughlin, W. A. Robinson and E. M. Wise. Iss. 12/30/52. App. 8/11/50 and 7/6/51. Assign. The International Nickel Co. of Canada, Ltd.

System of Airborne Conductor Measurements. An airborne electromagnetic-prospecting system in which the aircraft carries two orthogonal transmitting coils energized at different frequencies and a towed bird carries two orthogonal pickup coils parallel to the respective transmitting coils, the pickup coils being connected to discriminators whose responses are compared.

GRAVIMETRIC PROSPECTING

U. S. No. 2,613,536. J. J. Jakosky. Iss. 10/14/52. App. 7/30/46.

Gravity Meter. A gravimeter having a mass suspended from the middle of a nearly horizontal wire which is connected in a bridge circuit.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,614,432. R. T. Cloud. Iss. 10/21/52. App. 3/5/47. Assign. North American Geophysical Co.

Gravity Meter. A gravimeter in which the mass-supporting spring is in an electrical circuit and its impedance is measured and indicated or compared with the impedance of a similar adjustable reference spring.

U. S. No. 2,618,156. F. G. Boucher. Iss. 11/18/52. App. 12/31/49. Assign. Standard Oil Development Co.

Gravity and Density Gradiometer for Boreholes. A borehole gravity gradiometer having a suspended beam which carries a cross beam from each of whose ends is hung a pair of vertically-spaced masses, one of which is heavy and one light and the other pair being interchanged, rotation of the first beam about its own axis being observed.

MAGNETIC PROSPECTING

U. S. No. 2,615,957. F. W. Lee. Iss. 10/28/52. App. 6/17/48.

Temperature Compensation Magnetometer Indicator. A temperature compensating device for a balanced magnet type of magnetometer made of a sleeve surrounding the magnet and of different coefficient of expansion than the magnet, and held at one end by a bushing intermediate the middle and end of the magnet.

U. S. No. 2,615,961. W. J. Means. Iss. 10/28/52. Appl 12/7/46. Assign. Bell Telephone Laboratories, Inc.

Magnetic Testing System. A non-oriented total-field magnetometer having a flux-valve element mounted in a rapidly-rotating support so that it makes an angle whose cosine is $1/\sqrt{3}$ with the axis of rotation and with the flux-valve output squared and indicated.

U. S. No. 2,616,074. H. J. McCreary. Iss. 10/28/52. App. 4/10/50. Assign. Automatic Electric Laboratories, Inc.

Apparatus for Utilizing the Hall Effect. A Hall-effect magnetometer in which the Hall plate has highly-conductive wires imbedded in it or plated on its surface so that the resistance of the plate is reduced for a field intensity which will rotate the equipotential lines to the proper angle to be short-circuited by the wires but the resistance is unaffected when the equipotential lines are parallel to the wires.

U. S. No. 2,620,381. F. M. Mayes and A. J. Tickner. Iss. 12/2/52. App. 5/27/47.

Magnetometer Gradiometer Apparatus and Method. A magnetic gradiometer having a pair of spatially separated flux-valves with a field-detecting flux-valve located midway between them and with the output of the field detector used to control current in a neutralizing winding around each of the flux-valves.

RADIOACTIVITY PROSPECTING

U. S. No. 2,617,945. A. H. Lord, Jr. and E. Pancake. Iss. 11/11/52. App. 3/9/48. Assign. The Texas Co.

Prospecting Using Gamma Ray Detection. An airborne gamma-ray prospecting system in which the amplifier in the detecting system has its amplification controlled in proportion to the indication of an altimeter so as to automatically correct the gamma-ray indication for distance above ground.

SEISMIC PROSPECTING

U. S. No. 2,614,165. W. W. Doolittle. Iss. 10/14/52. App. 2/23/49 and 10/17/49. Assign. Stanolind Oil and Gas Co.

Marine Seismic Surveying. A marine seismometer spread in which the seismometers are spaced along the cable and with buoyant floats on the cable midway between them, so that the system rises to the surface when towing but allows the seismometers to sink below the zone of surface noise when at rest.

U. S. No. 2,614,166. R. G. Piety. Iss. 10/14/52. App. 4/24/50. Assign. Phillips Petroleum Co.

Method for Determining the Direction of Arrival of Waves. A directive seismometer having two modulator-type linear detectors excited in quadrature by a carrier with the modulated carriers combined and the phase of the resulting signal compared with the original carrier.

U. S. No. 2,614,228. J. A. Volk. Iss. 10/14/52. App. 10/5/49.

System of Seismographic Visual Recording. A recording system for earthquake seismographs in which the seismometer light beam falls on a photocell which is pulse excited and the photocell output amplified, demodulated, and recorded.

U. S. No. 2,615,521. T. C. Poulter. Iss. 10/28/52. App. 5/26/48. Assign. Institute of Inventive Research.

Apparatus for Seismic Exploration. A seismic exploration system in which the explosive charges are thin plates mounted horizontally above the surface of the earth a distance such that a shock wave of flat wave-front strikes the earth.

U. S. No. 2,615,522. T. C. Poulter. Iss. 10/28/52. App. 7/2/49. Assign. Institute of Inventive Research.

Seismic Exploration Employing Elevated Charges. A seismic exploration system in which elevated charges are fired so that the explosion produces a downward pressure on the ground for a time which is approximately one fourth the period of natural ground vibrations.

U. S. No. 2,615,523. T. C. Poulter. Iss. 10/28/52. App. 7/2/49. Assign. Institute of Inventive Research.

Seismic Exploration. A seismic exploration system in which elevated charges are fired in succession so that successive shock waves strike the ground separated by a time interval which is three quarters the period of natural ground vibration.

U. S. No. 2,615,524. T. C. Poulter. Iss. 10/28/52. App. 7/2/49. Assign. Institute of Inventive Research.

Seismic Exploration Employing Elevated Charges. A seismic exploration system in which elevated charges are so spaced that the downwardly-directed shock wave strikes the ground under the charges and the laterally-expanding shock waves from the charges combine to strike the ground with a time delay equal to three quarters of the period of natural ground vibration.

U. S. No. 2,618,999. D. H. Scott. Iss. 11/25/52. App. 9/8/48. Assign. The Texas Co.

Charge Setting Device. A jetting device for planting seismograph shots in silt and made of a pipe to which water is supplied, the lower section of the pipe being partially flattened so that the charge may be fastened to the flattened portion with tapes which are released by an external cable.

U. S. No. 2,619,186. C. H. Carlisle. Iss. 11/25/52. App. 1/24/48. Assign. Standard Oil Development Co.

Seismic Exploration Method. A method of eliminating interference due to secondary impulses from gas-bubble oscillation in underwater shooting by suspending a number of charges at the same depth and horizontally spaced so that gas bubbles break into each other and cause mutual distortion of the secondary impulses.

U. S. No. 2,620,890. B. D. Lee and G. Herzog. Iss. 12/9/52. App. 12/1/47. Assign. The Texas Co.

Seismic Prospecting. A seismograph recording system in which the geophone amplifiers modulate a high-frequency carrier which is recorded on a multi-channel magnetic record to be played back with pickups spaced to compensate for time differences and their outputs analyzed with filters and mixers.

U. S. No. 2,622,691. J. R. Ording. Iss. 12/23/52. App. 5/14/48. Assign. Standard Oil Development Co.

Seismic Exploration Method. A method of seismic exploration in water-covered areas using an auxiliary channel with a high-pass filter for recording water-borne compressional waves of frequency higher than the seismic waves recorded by geophone channels with low-pass filters.

U. S. No. 2,623,113. J. F. Bayhi and J. T. Baker. Iss. 12/23/52. App. 11/1/51. Assign. Standard Oil Development Co.

Seismic Prospecting with Optimum Geophone Coverage. A seismograph mixing system using cathode-follower circuits with their grids connected to the geophones whose signals are to be mixed and with a common cathode resistor.

U. S. No. 2,623,922. G. Muffly. Iss. 12/30/52. App. 4/17/50. Assign. Gulf Research & Development Co.

Electric Pulse-Forming Shot-Firing Device. A seismograph shot-firing device having a generator which charges a large condenser connected by a switch to the firing circuit through resistors which assure a short current pulse and coupled to the shot-moment circuit through a saturable-core reactor.

U. S. No. 2,623,938. M. E. Thomas. Iss. 12/30/52. App. 3/21/49. Assign. Phillips Petroleum Co.

Seismometer. A moving-coil electromagnetic seismometer having an annular magnetic-air gap and a coil which is suspended in the air-gap by a system of torsion wires.

U. S. No. 2,623,947. J. J. Roark. Iss. 12/30/52. App. 9/29/47. Assign. Standard Oil Development Co.

Phase Correction Filter Circuit. A filter for a seismograph amplifier in which a constant time delay for all frequencies of a transient is achieved with a band-elimination type of filter whose signal output is amplified and part of it combined with the filter input through a voltage divider adjusted to a desired phase-angle intercept.

WELL LOGGING

U. S. No. 2,613,746. C. E. Whitney. Iss. 10/14/52. App. 4/23/48. Assign. Baker Oil Tools, Inc.

Collar Locating and Tool Operating Device. A mechanical casing collar locator having leaf springs which flare upwardly and outwardly to catch in the collar recess but which are retracted by a sleeve when upward tension is applied.

U. S. No. 2,614,164. O. H. Huston. Iss. 10/14/52. App. 11/12/47. Assign. Schlumberger Well Surveying Corp.

Mutual Inductance System. A telemetering system in which a moving core changes the mutual inductance of two coils, the primary coil being excited by current of saw-tooth wave form so that it has a constant rate of change and the secondary voltage synchronously rectified and measured.

U. S. No. 2,615,248. A. B. Hildebrandt. Iss. 10/28/52. App. 4/21/51. Assign. Standard Oil Development Co.

True Dip Determining Apparatus for Well Logging. A geometric apparatus for reproducing the true attitude of a horizon from three azimuthally-spaced records obtained by a well-profile logging instrument.

U. S. No. 2,615,779. P. E. Chaney and W. E. Barnes. Iss. 10/28/52. App. 10/26/45. Assign. Sun Oil Co.

Driving and Recording Mechanism for Calipering Devices. A calipering device having a roller which drives a record drum and another roller on an outwardly-pressed arm connected to a stylus which records on the drum, and a latch for lifting the stylus when the record is completed.

U. S. No. 2,615,956. R. A. Broding Iss. 10/28/52. App. 1/5/51. Assign. Schlumberger Well Surveying Corp.

Borehole Telemetering. A system for indicating at the surface the unbalance of a bridge circuit in the well independent of cable impedance and in which excitation is supplied from the surface at one frequency and returns to the surface as a frequency-modulated signal indicative of bridge input and also returns to the surface on a different frequency as a frequency-modulated signal indicative of bridge output, the signals being demodulated at the surface and their phase relations compared to indicate the bridge input and bridge output.

U. S. No. 2,617,852. H. C. Waters. Iss. 11/11/52. App. 2/10/50. Assign. Perforating Guns Atlas Corp.

Electrical Well Logging System. A system for making several electric logs over a three-conductor cable in which the exciting a–c is fed down the cable and the logging signals are rectified in the well apparatus and returned as d–c and recorded on low-impedance galvanometers so as to minimize variations in cable resistance and capacity.

U. S. No. 2,617,941. D. E. Craggs. Iss. 11/11/52. App. 2/17/50. Assign. Union Oil Co. of California.

Measurement of Fluid Flow in Boreholes by Radioactivity. A system for flow logging a well by injecting a small amount of radioactive tracer at a known point in the well and observing the time of its arrival at a number of vertically-spaced radioactivity detectors.

U. S. No. 2,618,156. F. G. Boucher. Iss. 11/18/52. App. 12/31/49. Assign. Standard Oil Development Co.

Gravity and Density Gradiometer for Boreholes. For abstract see GRAVIMETRIC PROSPECTING.

U. S. No. 2,620,386. P. L. Alspaugh and G. Cook. Iss. 12/2/52. App. 1/12/50. Assign. Union Carbide and Carbon Corp.

Earth Strata Cutting Indicator. A device which indicates on a c-r tube screen the variation in character of vibration in the tooth of a mining machine as it cuts through various rock strata.

U. S. No. 2,620,658. R. G. Piety. Iss. 12/9/52. App. 8/9/48. Assign. Phillips Petroleum Co.

Thermal-Electric Flowmeter for Fluid Flow Measurement in Boreholes. A subsurface flowmeter having an electrically-heated resistance element at each end of a rocker arm in the flow stream, the arm being oscillated by an electric motor, and the resistance elements connected in a bridge circuit whose alternating unbalance signal is amplified and recorded at the surface.

U. S. No. 2,622,124. T. R. Homer. Iss. 12/16/52. App. 9/13/48. Assign. Lane-Wells Co.

Electrical Logging in Well Bores. An S-P logging system having an elongated auxiliary electrode spaced a short distance above or below the logging electrode but not connected to the potential-measuring circuit.

U. S. No. 2,622,334. B. F. Wiley. Iss. 12/23/52. App. 3/4/49. Assign. Phillips Petroleum Co.

Logging Caliper. A caliper-logging device having arms which are geared to a common shaft actuating a variable resistor, the shaft having a spiral spring to urge the arms outward and an electrically-released latch for holding the arms in a retracted position when entering the borehole.

U. S. No. 2,622,339. J. C. Hewitt, Jr., Iss. 12/23/52. App. 5/16/49.

Battery Energized Well Instrument. A well instrument having a pressure-sealed instrument compartment and a dry-battery container in which the battery is subjected to the pressure of the well fluid so as to permit operation at high well temperatures.

U. S. No. 2,622,694. R. C. Pryor. Iss. 12/23/52. App. 8/2/48. Assign. Phillips Petroleum Co.

Gas Extraction Apparatus. A steam extractor for removing hydrocarbon gases from drilling mud in which the mud flows upward past steam jets and then past baffles where water is introduced.

U. S. No. 2,623,805. B. W. Sewell. Iss. 12/30/52. App. 9/7/46. Assign. Standard Oil Development Co.

Well Logging Apparatus. A well-logging system in which a magnetizable wire is suspended in the well and the logging device arranged to travel along the wire and magnetically record its signal on the wire.

U. S. No. 2,623,923. C. W. Zimmerman. Iss. 12/30/52. App. 4/23/51. Assign. Schlumberger Well Surveying Corp.

Electrostatically Shielded Magnetic Well Logging System. An electromagnetic-logging system having in the well a long solenoid connected in an a-c bridge circuit with the solenoid electrostatically shielded by a split, non-magnetic, grounded, conducting cylinder with similar longitudinal fins.

MISCELLANEOUS

U. S. No. 2,613,250. H. L. Bilhartz and H. F. Dunlap. Iss. 10/7/52. App. 10/6/50. Assign. The Atlantic Refining Co.

Method for Measuring Resistivity of Earth Samples. For abstract see ELECTRICAL PROSPECTING.

U. S. No. 2,613,531. C. G. Bacon. Iss. 10/14/52. App. 11/14/44. Assign. U. S. A.

Diffusion Measuring Meter. A device for measuring porosity at low pressure in which the sample is placed in the flow tube between a vacuum pump and a leak port and the volume of gas measured which enters the system from a chamber ahead of the leak port.

U. S. No. 2,616,177. W. O. Bazhaw. Iss. 11/4/52. App. 11/3/47.

Apparatus and Method of Surveying Elevations. A surveying apparatus having a camera which may be leveled and which photographs targets of known position on a distant rod together with the compass bearing.

U. S. No. 2,617,296. J. D. Wisenbaker. Iss. 11/11/52. App. 12/20/46. Assign. Core Laboratories, Inc.

Process for Treating Core Samples. A process for preserving core samples when removed from the ground by cleaning off excess drilling mud and immersing the sample in dry ice.

U. S. No. 2,617,719. C. R. Stewart. Iss. 11/11/52. App. 12/29/50. Assign. Stanolind Oil and Gas Co.

Cleaning Porous Media. A method of cleaning cores in which a solvent containing dissolved gas at high pressure is forced into the core and then the pressure suddenly released to below the bubble point so that the released gas will force solvent and other fluids out of the pore spaces.

U. S. No. 2,618,151. W. J. Leas. Iss. 11/18/52. App. 10/7/48. Assign. Standard Oil Development Co.

Cell for Measuring Relative Permeability. A cell for measuring the permeability of a core and having a rubber sleeve pressed against the outer surface of the core and porous discs pressed against the ends of the core with two flow tubes at each end, one tube leading to the porous disc and the other one passing through the disc and leading to the end of the core.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE FOURTH QUARTER OF 1952

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2,612,774	428	2,614,249	16	2,615,935	160
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2,613,250[a]	124, 88	2,614,425	148	2,616,074[a]	232
2,613,261	484	2,614,426	200	2,616,077	316
2,613,273	12	2,614,427	200	2,616,078	316
2,613,283	484	2,614,428	188	2,616,079	312
2,613,302	188	2,614,432[a]	180	2,616,177[a]	444
2,613,317	316	2,614,572	200	2,616,187	520
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2,613,323	236	2,614,760	224	2,616,294	200
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2,613,327	308	2,614,900	324	2,616,640	312
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REVIEWS

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Seismic Prospecting for Oil, by Charles Hewitt Dix, Harper & Brothers, New York, 1952, xx+414, pp. $7.50.

In fulfilling the purposes to which this volume is dedicated, it is complete in subject matter, adequate in presentation, well-supplied with excellent figures and of superb format. It will therefore serve quite satisfactorily as a reference book for seismic computers and as a text for elementary instruction in seismic exploration.

Each of the five "Parts" of the book is subdivided into several chapters and the whole forms a continuity which is pleasing to follow. In fact, the Table of Contents, itself, constitutes a complete outline of seismic prospecting (for oil): its fundamentals, its background, its elementary theory, its routine operations and its economics. In the discussion of actual procedures of seismic exploration —and in some other details—one might, of course, differ here and there with the author, but in his discussion of the physical principles involved, the author has succeeded in rendering an excellent and

satisfying, though simplified, picture of the physical and mathematical elements of seismology.

The technical student of mature development will find the book lacking in scholarly approach. The reviewer is disappointed in the looseness of the text from the editorial standpoint, knowing the scholarship of the author and the prestige of the publisher. Particularly does the book show the effects of trying to write the text around the figures, excellent as they are, in which the mathematical developments are contained. Presumably this method of writing was designed to save the large expense of mathematical typesetting, but the consequences were disastrous for the serious student insofar as these mathematical developments were concerned.

The book will find a wide and an appreciative audience among the interpretation staffs of exploration groups and among the many young people in school interested in seismic prospecting. In fact, all people engaged in the exploration for oil would do well to read the book.

M. M. SLOTNICK
Humble Oil & Refining Company

Proceedings of the Fourth Empire Mining and Metallurgical Congress, Great Britain 1949, Parts I and II, edited by F. Higham, Offices of the Congress, London, 1950, 1139 pp., £2.

The chief object of the Empire Mining and Metallurgical Congress is "to afford an opportunity for mining engineers, metallurgists, scientists, engineers, and others concerned with the mining and metallurgical industries to meet and discuss technical progress and problems, including the development of the mineral resources of the British Commonwealth of Nations."

This Congress, the fourth of a series beginning in 1924, was held in London in July, 1949. These two volumes give a complete account of the speeches and technical papers that were given. The present review is confined to those topics of major interest to the geophysicist.

In his opening presidential address, Sir Henry Tizard, Minister of Fuel and Power of Great Britain, emphasizes that in the search for mineral deposits today, "the normal studies of the geologist do not give sufficiently accurate information about deposits at great depth. . . . The mining geologist must now become an applied physicist and make use of all the technique that physicists can supply." In a plea for more fundamental research in geophysics, he states that " . . . such an applied science cannot yield its greatest dividends unless it is always being developed on a firm foundation of fundamental knowledge. We need to encourage and stimulate the basic science of geophysics."

The technical papers are grouped under seven main headings: modern methods of prospecting (4 papers); mineral resources (9); petroleum (2); coal (3); present-day trends in mineral dressing (4); metallurgy and metallurgical industries (12); and physiological and psychological effects of heat and humidity on workers in deep mines and metallurgical works (6).

The four papers concerning modern methods of prospecting are of special interest to the geophysicist. One paper, "Aerial Photography in Petroleum and Mineral Prospecting," by A. A. Fitch, D. F. Christie, W. E. Johnstone, and G. Whittle, discusses in some detail methods of flying, technique of interpretation, and commercial applications, including examples of photogeologic maps of parts of Sumatra, Pakistan, southern Palestine, Gulf of Aqaba, and Skye.

A second paper, "Modern Methods of Mineral Exploration in South Africa," by L. T. Nel, D. J. Simpson, and J. de Villers, states that "the production of a geologic map—the more detailed the better—and the application of geological knowledge and methods, assisted by aerial surveys, geophysics, geochemistry and other new techniques, based upon scientific principles, as auxiliary tools, offer the best means of finding new ore bodies." Geophysical methods that have been used successfully in South Africa are discussed. In the Witwatersrand and Orange Free State gold fields, for example, the Witwatersrand system, which carries the auriferous conglomerates, is ideally suited for mapping by magnetic measurements as the lower portion of this system is composed of several magnetic shale band markers which maintain their magnetic characteristics over the whole developed length of the system and can be detected at considerable depth. In the area south of Klerksdorp, Orange Free State, geological and geophysical exploration (by magnetic and gravimetric methods), followed by

deep drilling, has located Witwatersrand reefs carrying payable values at a sufficient number of places that the establishment of several large mines in the area so far prospected can be expected. An airborne magnetometer survey also has discovered "encouraging anomalies" in an area far west of the recognized Orange Free State gold field. In coal field problems in South Africa, magnetic measurements are of considerable use in delineating the post-Carboniferous dikes which have burned considerable areas of coal on their flanks and in delineating areas underlain by lavas as opposed to sedimentary formations, with resulting saving in drilling costs.

A third paper, "Modern Methods of Mineral Exploration in Canada, "by F. R. Joubin, contains many excerpts from A. A. Brant's paper, "Some Limiting Factors and Problems of Mining Geophysics, with Particular Reference to Canadian Conditions," published in *Geophysics*, October 1948. Several ore bodies discovered or indicated recently by geophysical work in Canada are discussed.

In a fourth paper, "Mineral Exploration in Australia," C. J. Sullivan, Superintending Geologist, Australian Bureau of Mineral Resources, Geology and Geophysics, states that "in the past decade, geophysical investigation has become indispensable and air-photography is used for regional geological mapping wherever possible. Geochemical studies are only now beginning in Australia but initial work suggests that this science will add greatly, both to fundamental knowledge of ore genesis and to the techniques of actual search." In areas where the ore deposits are of the lode or fissure type and are not related to the replacement of particular beds, the extensive geologic and geophysical exploration has not so far yielded encouraging results. In the Cobar-Nymagee area, New South Wales, for example, in which chalcopyrite is associated with pyrrhotite, a large magnetic anomaly and self-potential anomaly were found and outlined, but subsequent drilling has as yet revealed only a low-grade (2 percent) pyrrhotite deposit. In the Broken Hill district, New South Wales, extensive geologic mapping and thorough magnetometer and gravimetric surveys are being made in an attempt to find another complete Broken Hill lode. Structures similar to that at Broken Hill have been found, but whether these structures contain ore is not yet known.

In discussions that follow the presentations of the above four papers, additional information concerning modern methods of prospecting is offered by visiting scientists and engineers. In Egypt, "Geophysics . . . was of tremendous help in the war (World War II), particularly for the armies in the Middle East. There the geologist and the geophysicist managed to make the Egyptian campaign a success mainly on the aspect of water."

In Tanganyika, in the search for water, "with the aid of the geophysicist we have now reached the stage of getting three effective boreholes out of every four, whereas previously it was one out of every three."

In Nigeria, geophysical and geochemical surveys have been made to assist in the search for veins of lead-zinc-silver ores.

In India, geophysical surveys to date have consisted principally of magnetic exploration for manganese ore (in which magnetite occurs as a constituent mineral) in the Central Provinces and, to a limited extent so far, exploration for water. In one area that was covered by a 60 to 70-foot mantle of alluvium, a geophysical survey successfully delimited an area of coal-bearing rocks that was "let down" (faulted?) and completely surrounded by an area of pre-Cambrian gneisses and thus indicated the area desirable for drilling for coal, although the coal seams themselves were not detectable by geophysical methods.

In the group of papers concerning mineral resources, each paper deals with the principal resources of a separate country or group of countries within the British Commonwealth. Papers discussing the mineral resources of Australia, India, Southern Rhodesia, Malaya, British West African Colonies, and East African Colonies are included. Mineral maps, recent production figures, and brief discussions of the geologic settings of the principal ore deposits accompany most of the papers.

Of the two papers dealing with petroleum, one is "Modern Drilling and Production Practice in the Oil Fields of South Iran," by H. W. Lane. Many special precautions are necessary in drilling wells in these "high pressure, well-fissured limestone reservoirs" ("undoubtedly the largest limestone fields in the world"); and special production techniques, such as recycling and the multistage method

of separating gas from crude oil, are employed in these wells, which have the highest producing rate in the world, the average over all the fields being 10,000 bbl per day per well while individual wells can produce as much as 32,000 bbl per day. The geologic column of the area, as well as cross sections of several Iranian oil fields, are given.

The other paper dealing with petroleum is "The Application of Auger and Core Drilling in Petroleum Exploration," by N. J. M. Taverne. Examples of the usefulness of shallow hand augering (15 to 25 ft) and deep hand augering (120 to 180 ft) in determining geologic structure are presented. The use of widely spaced reconnaissance or pilot test holes for checking gravity interpretation is illustrated, and the application of ocean-floor sampling core drilling for checking and supplementing the data obtained by offshore seismic surveys for oil is discussed briefly.

As a compendium of recent knowledge concerning the modern methods of prospecting, mineral resources, and present-day trends in mining and metallurgical techniques in the British Commonwealth, the volumes are highly recommended.

KENNETH L. COOK

Electronic and Ionic Impact Phenomena, by H. S. W. Massey and E. H. S. Burhop, Clarendon Press, Oxford, 1952, 669 pp., $14.00.

This book addresses itself primarily to the study of experimental techniques in impact phenomena. The theory, where the authors do give it, is used in a supporting role. The subject matter, as they say, is sufficiently extensive that, even in as large a book as theirs (669 pages, including index and table of contents), selectivity is essential, or the volume of the writing would get out of control.

The book seems to contain nearly everything somewhere within its covers. Even the recent anomalous results on recombination of electrons and positive ions in plasmas of rare gases or alkali metals are found in the back of the book. The treatment is orderly in the sense that related phenomena are grouped together. This type of treatment leaves the disadvantage that other groupings are more difficult to pursue. For example, a reader, desiring to compile a detailed list of the properties of argon in regard to its connection with impact phenomena, would be helped only in the index, not through the organization of Massey and Burhop's book as it appears in the table of contents. From reading of related classic texts in germane fields of study, this reviewer is convinced that the subject matter of *Electronic and Ionic Impact Phenomena* is extremely difficult to organize in a manner that would exactly fit the needs of workers in all fields of pure and applied science. The complexity and volume of the experimental data covered in this book required care in presentation to permit emphasis of credible data and yet not disregard results of possible value. The authors have succeeded in maintaining a well balanced critical attitude. This reviewer is very happy to see a new text of such a scholarly character.

Certainly, it is too much to expect that this subject could be properly presented and retain easy reading qualities of modern fiction. The reader is assured that *Electronic and Ionic Impact Phenomena* is not a book which is so presented, and, indeed, this book is not for the casual reader but is a work of reference, designed primarily for the instruction and for the serious student in the field. The book is replete with references which are distributed in such a manner as to be close to the pertinent text, not grouped at the ends of the chapters, as is the case in certain other fields of technical writing. The reviewer was inclined to like this arrangement. The book is cloth bound and has outside dimensions of $9\frac{3}{4}$ inch $\times 6\frac{1}{2}$ inch $\times 1\frac{7}{8}$ inch. The pages are smooth paper and are $9\frac{1}{4}$ inch $\times 6$ inch. The type is easy reading. The binding of the volume is not designed to withstand rough use, but probably is satisfactory for service in a reference library.

Considering everything, this book would undoubtedly be worth the $14.00 price, for which it is sold, if the buyer had a serious need for a recent text in the field.

ROBERT E. FEARON
Well Surveys, Inc.

"A Gravimeter Survey in the Bristol and Somerset Coalfields," by A. H. Cook and H. V. S. Thirlaway, *Quarterly Journal of the Geological Society of London*, London, England, Vol. CVII, Part 3, Aug. 1952. pp. 255–286.

"The Results of a Gravity Survey in the Country between the Clee Hills and Nuneaton," by A. H. Cook, J. Hospers, and D. S. Parasnis, *Quarterly Journal of the Geological Society of London*, London, England, Vol. CVII, Part 3, Aug. 1952, pp. 287–307.

These two papers by members of the Department of Geodesy and Geophysics at Cambridge University, England, deserve critical reading by interpreters of geophysical and, in particular, gravity data. They are among the first, outside of company reports, which are confidential, in which techniques borrowed from the field of statistics are employed to correlate geologic structure with the gravity picture. By means of scatter diagrams showing plats of gravity variations against thickness variations of a formation or series of beds, calculations of standard deviations, regression lines and coefficients of correlation, attempts are made to establish quantitative relationships between these variables taking into account not only the variability of the data itself but also its quantity.

In these two papers much consideration is also naturally given to the probable densities, in place, of the formations believed involved in the creation of the gravity anomalies. Density data from laboratory tests of samples, and from field tests with the gravity meter over hills and down mine shafts are discussed. The statistical approach is also tried to determine the probable contrast at the first density interface in one area.

From the extensively reported discussion which followed the presentation of the papers before the Society it is evident that some well-known geologists and geophysicists at the meeting were not sure that the authors had not carried the purely mathematical manipulations farther than the geologic data available justified.

It would appear to the reviewer that the statistical techniques described in these papers are useful additions to methods of interpretation. However, in using them one must be on guard to consider critically the quality of the geologic "facts" which are accepted and platted as of equal certainty against the gravity measurements, which can usually be obtained with a high degree of accuracy. In most areas where gravity surveys are believed useful in extending our knowledge of structure, data on the thickness of formations and their constancy of density are usually very small compared to the gravity data available. Thus, the scatter diagram may have relatively few points and the coefficient of correlation may be far from representative of the true conditions. Forcing a quantitative relationship between the geological and gravity data by means of a regression curve ignores the possibility that much of the variation in gravity over the area really has its origin at depths far below the beds under consideration. It is very possible that, over sizable areas in some parts of the world, the gravity variations due to density variations in the older sediments and in the igneous-metamorphic basement complex may be unimportant, but this has not been the reviewer's experience. The recently published airborne magnetometer surveys known to the reviewer over vast and otherwise virtually inaccessible areas of pre-Cambrian outcrops in Canada and the United States have certainly indicated that pronounced changes in rock character are the rule and not the exception. While it does not follow that every change in rock character betrayed by strong changes in rock magnetization necessarily is accompanied by a change in density, still enough such changes do exist to make anomalies of intrabasement origin always a source of uncertainty in deriving simple mathematical relationships between formation thickness or formation depth and gravity variation. It would appear that companion magnetic surveys over areas covered by gravity surveys would always offer some help in determining the amount of gravity variation likely due to these deep sources.

ROBERT J. WATSON

"Gravity and Magnetic Reconnaissance Roma District, Queensland," by J. C. Dooley, *Bureau of Mineral Resources, Geology and Geophysics*, Commonwealth of Australia, Bull. No. 18, 1950, 24 pp., 7 plates.

This is a concise and well written report and is of unusual interest. The author has gone to the trouble to examine all the available literature on the area and has presented a complete history including early discoveries, geology, magnetic susceptibilities, and density data.

Interest in the Roma area as a potential source of oil and gas dates back to the year 1900 with the discovery of natural gas in a government water well. Since that date there has been ever increasing activity. At the time this report was written, there had been at least thirty test wells drilled and some 230 "scout bores" in the area. Considerable flows of natural gas and small quantities of oil have been found in many of the wells, but no major commercial supplies have been developed. Some geophysical work had been done in this area in 1927–1929, but no useful results were obtained since the work was confined to local testing of various places.

The geophysical work covered in this report consists of some 730 gravity and magnetometer stations which were run simultaneously in December, 1947 and from June to December, 1948. Results of the gravity survey are presented as reduced gravity, regional gravity, and residual gravity maps. Probably the most significant result of the gravity work is that regional gravity does not agree with the known basement configuration. Information on basement structure was obtained from drilling logs of the thirty odd deep wells drilled in the area. They reveal a broad plunging anticline whose axis is NW-SE. The basement of the area is approximately 3,000–4,000 feet beneath the surface. From density information available the author concludes that major features in the gravity contour pattern are caused by deep-seated variation in the basement complex.

Results of the vertical magnetometer are presented as a reduced contoured map. It is evident that magnetic trends and anomalies cannot be correlated with known basement topography. The author believes that magnetic anomalies may be associated with outcrops of ferruginous rocks and that further application of the magnetic method might be useful in mapping structure in the near surface sediments.

The author has recommended that the seismic method be used if it should be found applicable. There are two local gravity highs which apparently have their origin in the sediments and these have been recommended as "targets for beginning the seismic survey."

There are seven plates in this report which show the final results of the survey. Included are several gravity maps (including reduced, regional, and residual gravity with different pattern spacing), a magnetic map, basement contour map, and geologic cross sections with gravity and magnetic profiles.

EUGENE FROWE

"Gravity and Magnetic Investigation of the Structure of the Cortlandt Complex, New York," by Nelson C. Steenland and George P. Woollard, *Bulletin of the Geological Society of America*, Vol. 63, Nov., 1952, pp. 1075–1104.

This paper affords an example in which careful quantitative analysis of the gravity and magnetic data, including the determinations of the density and magnetic susceptibility of rock samples in the surveyed area, assists in the study of a complex geologic problem.

The Cortlandt Complex consists of an unusual body of igneous rocks (norite, diorite, and pyroxenite) lying within metamorphic rocks and granites along the east bank of the Husdon River near Peekskill, New York. Embracing an area of about 24 square miles, this igneous complex is characterized by (1) an unusual suite of basic rocks, (2) a systematic zoning of rock types, (3) a conspicuous banding locally of alternating light and dark minerals, and (4) a suggested funnel shape to the pluton as a whole, with postulated subsidiary funnel-shaped bodies within the interior. As a geologic curiosity and challenge and as an economically important host to emery deposits, the complex has been investigated periodically for over half a century by many eminent geologists.

During 1946 and 1947, gravity and magnetic surveys were made to determine (1) whether the complex represents one or more distinct lithologic units and (2) what their shapes are beneath the surface. Observations were made at 185 stations, which averaged about three stations per square mile. About one-third of these stations were located over the exposed rocks of the complex. Both

gravity and magnetic measurements were taken at all the stations. Askania vertical magnetometers were used for the magnetic measurements, and both a Frost gravimeter and a Humble X-type gravity meter were used for the gravity measurements.

The gravity data were reduced in the usual manner to give simple Bouguer gravity anomalies. Elevations of the stations are considered accurate to within two feet. A "first residual" gravity map was compiled by a profile method in which both north-south and east-west profiles were constructed over the Bouguer anomaly map at 1-mile intervals.

The first residual gravity map, contoured at 5-mgal intervals, shows a pronounced gravity anomaly of about 30 mgals. The maximum circular-shaped contours lie over the olivine pyroxenite that constitutes the eastern part of the complex. A smaller anomaly of about 15 mgals lies over an area of exposed augite norite and norite with prismatic hornblende that constitutes the southwestern part of the main pluton. Although the larger gravity anomaly corresponds in position with one of the foliation structures mapped by Balk within the complex, no separate gravity anomaly occurs over the central part of the complex, where a dominant foliation structure exists with almost perfect zoning of rock types.

The bulk density and magnetic susceptibility values of 26 rock samples of the complex and nine samples of the surrounding country rock were determined and contoured on separate maps. The density distribution within the complex conforms in general to the Bouguer gravity-anomaly pattern. Using an indicated average density contrast of 0.4 gm/cc between the pluton and the country rock, theoretical bodies that would satisfy the observed anomalies were calculated. The larger anomaly of 30 mgals is closely approximated by a vertical cylinder 2.4 miles in diameter and 4.7 miles thick, and the smaller anomaly of 15 mgals is approximated by a vertical cylinder 1.2 miles in diameter and 5.0 miles thick. The thicknesses are minimal values because infinitely long cylinders of the same cross sections have essentially the same gravity effect.

A "second residual" gravity map, obtained by removing the gravitational field of the two theoretical cylinders from the first residual gravity map, shows a "second residual" gravity anomaly of 8 mgals in the area lying between the cylinders and suggests that here the rocks of the complex are about 0.3 mile thick. Smaller second residual anomalies on this map lie over small outcrops of rock typical of the Cortlandt series exposed in the area west of the Hudson River and suggest the existence of small, separate feeder pipes at two localities.

Thus the gravity data, used in conjunction with the known geology, suggest that the Cortlandt series consists of a relatively thin sheet of igneous material that was derived largely from two main vertical feeder pipes that extend to a depth of five miles at least. The magmatic pipes lie near the eastern and southwestern margins, respectively, of the main pluton. Two, and possibly three, subsidiary feeder pipes lie at or near the west margin. The material in all the pipes is apparently basic, and the relatively thin sheet of igneous rock forming the central part of the complex consists apparently of norite and poikilitic hornblende.

The magnetic map shows no general anomaly associated with the complex as a whole or with either of the main gravity anomalies in particular. A broad magnetic anomaly of 1,200 gammas, situated centrally within the complex, is ascribed to an anomalous concentration of magnetite in the host rock beneath the complex and affords a basis for estimating the depth to the host rock, 0.3 mile. This depth conforms to the order of magnitude of the thickness of the complex as determined from the gravity data.

Four local anomalies of approximately 1,000 gammas lie at or near the margin of the complex. Of these, three anomalies correlate with known bodies of magnetite-bearing emery.

Mindful of the ambiguity of gravity and magnetic data, the authors have synthesized a picture in which the geological and geophysical data correlate on the whole. To explain the principal inconsistency, involving Balk's central funnel, which Shand believes is the primary source of the rocks forming the complex, the authors suggest a downward, rather than an upward, emplacement of the central part of the complex. The downward emplacement is postulated as resulting from (1) subsidence during emplacement or (2) "gravity filling of pre-existent surface depressions by extruded material."

KENNETH L. COOK

"Allard Lake Ilmenite Deposits," by Paul Hammon, *Economic Geology*, Vol. 47, No. 6, Sept.–Oct., 1952, pp. 634–649.

The airborne magnetometer was used in the exploration of the Allard Lake ilmenite deposits which includes the Lac Tio deposit, " . . . the largest body of titanium ore of its type now known. . . ." A negative magnetic anomaly with an approximate maximum relief of 3,500 gammas was resolved over the Lac Tio body. On the other hand, the anorthosite mass, which includes the Lac Tio body, exhibited a relatively uniform magnetic pattern with some local anomalies of between 2,000 and 4,000 gammas over areas of disseminated ilmenite.

The anorthosite mass lies roughly parallel to the Pre-Cambrian-Paleozoic contact on the southern edge of the Canadian shield. This large mass is about 90 miles in length and 20 to 30 miles in width. It varies from almost pure feldspar rock through anorthositic gabbro, ilmenite-rich anorthosite, and norite. The Lac Tio deposit is considered to be approximately square, with sides of 3,500 ft. Diamond drilling has disclosed that the vertical depth is several hundred feet, with some of the holes stopped in ore at 300 ft. The ore is actually ilmenite-hematite, with high grade ore containing " . . . 75 percent ilmenite, 20 percent hematite, with the remainder being . . . pyroxene, feldspar, and minor amounts of pyrite, pyrrhotite, and chalcopyrite." The ore body is thought to be late magmatic in origin, having been derived from disseminated ilmenite, present in the anorthosite, that became concentrated during extremely slow consolidation by the elimination of plagioclase and pyroxene during late gravitative liquid accumulation.

The magnetic survey did not discover any new deposits but did delineate the Lac Tio body with a large negative anomaly. Approximate calculations indicate that the ore must have a magnetic susceptibility of the order of .07 cgs and must be negatively polarized to produce the negative anomaly. The negative polarization was confirmed by dip-needle work.

This is another example of the negatively polarized igneous rock bodies that are becoming increasingly common as magnetic surveying becomes more widespread. In this instance, there is a suggestion that the reversal in polarization occurred in a body of rock that was undergoing slow consolidation while simultaneously surrounded by a previously consolidated host rock of high magnetization and apparently normal polarization. This phenomenon of induced reversed polarization should be investigated quantitatively, especially in the case of this ore body where many of the unknown geologic factors have been determined.

NELSON C. STEENLAND

"A New Permanent Magnet from Powdered Manganese Bismuthide," by Edmond Adams, William M. Hubbard, and Albert M. Syeles, *Journal of Applied Physics*, Vol. 23, Nov., 1952, pp. 1207–1211.

Geophysicists interested in permanent magnet materials will find this article of considerable importance. The investigation of magnetic material composed of magnetically aligned crystals of Mn Bi was suggested to the authors by Dr. G. W. Elmen and the work was carried out in the Naval Ordnance Laboratory at White Oak, Silver Spring, Maryland. The material has been called Bismanol, and the process and product is a property of the United States government. Application for license under a pending U. S. patent application may be made to the Chief of Naval Research, Washington 25, D. C.

A maximum energy product (BH) max as high as 4.3×10^6 gauss-oersteds was achieved with the possibility of still higher values. The coercive force (H_c) of 3,400 oersteds is exceeded by no other known practical magnets. (Compare with 580 for Alnico V.) Rather complete descriptions of the method of fabrication are given and it would appear from the comparatively low pressures and temperatures used that the fabrication of the magnets could be done in almost any laboratory. A small amount of free Bismuth at 300° C. provides a fluid medium in which to align the crystals and, after solidification upon cooling, to separate and immobilize the particles.

NORMAN RICKER

"The Occurrence of Hydrocarbons in Recent Sediments from the Gulf of Mexico," by Paul V. Smith, Jr., *Science*, Vol. 116, No. 3017, Oct. 24, 1952, pp. 437–439.

The most thorough study of the occurrence of hydrocarbons in recent sediments heretofore published appeared in A.A.P.G. Bulletin 32, 1934, a report of the work done by the group headed by Parker D. Trask under A.P.I., Project 4. That group did not find any liquid hydrocarbons in quantities greater than 1 part per 100,000 among 2,000 samples from all parts of the world.

Paul Smith has been investigating the nature of organic matter in recent sediments under a project initiated several years ago by the Standard Oil Co. (New Jersey). He has extracted organic matter in a range of from 30 to 450 parts per 100,000 and the quantity of hydrocarbons varied from 2 to 19 parts per 100,000.

This short paper on Mr. Smith's results is a distinct contribution to the understanding of the formation of hydrocarbons and also to the methods of laboratory analysis.

NELSON C. STEENLAND

"Uranium in the Clay of a Black Radioactive Shale," by James H. Brown, Jr., and W. D. Keller, *Science*, Vol. 116, No. 3023, Dec. 5, 1952, pp. 632–633.

Increased attention is being requested of the geophysical profession to co-operation in the search for radioactive minerals. In this connection, brief notice should be given to Brown and Keller's short paper on the occurrence of uranium in shale.

The shale investigated was a thin, black layer in the Spergen limestone just north of Ste Genevieve, Mo., which contained uranium and vanadium. The authors found the uranium in the fine clay fractions and not in the black, organic material of the shale. Their results tend to refute earlier opinions which held that uranium in shale would reside primarily with the carbon that was present.

NELSON C. STEENLAND

"On Dispersion Curves of Surface Waves from the Great Assam Earthquake of September 15, 1950," by T. Akima, *Bull. Earthquake Res. Inst.*, Tokyo Univ., Vol. XXX, Part 3, 1952, pp. 237–258.

For more than a quarter of a century, seismologists have used the dispersion of Love waves and Rayleigh waves from earthquakes to estimate the thickness as well as the composition of the earth's crust. In the past, all such studies have been either for the Love waves or the Rayleigh waves of a given earthquake but never for both. In the Assam earthquake, one of the most intense of recent years, the seismograph stations in Japan were located almost due east of the epicenter, so that records from the east-west horizontal seismometers showed only Rayleigh waves and those from the north-south instruments, only Love waves. It was thus possible to study the dispersion characteristics of both types of waves. Therefore, this paper, reporting on these studies, gives the first published comparison of Love wave and Rayleigh wave dispersion data from the same earthquake.

Observation of the long-period surface waves was facilitated by the introduction of a low-pass torsion pendulum filter which removed the high-frequency "noise" superimposed on the Love waves and Rayleigh waves. This procedure, which is of course similar to the filtering of seismic reflection records, has not been employed, to this reviewer's knowledge, on earthquake records elsewhere.

Group velocities of both wave types were measured as a function of period on records from seventeen earthquake stations across the Japanese islands. Systematic differences in the curves obtained at the southern stations and the northern ones were interpreted to indicate that the crustal structure under the East China Sea is different from that under the Sea of Japan.

Comparison with theory showed that for the waves received at the northern stations, an assumption of a single crustal layer 27 km thick and 5.9 km/sec in compressional velocity underlain by material with a compressional speed of 7.3 km/sec fits the dispersion observed both in the Rayleigh waves and Love waves. For the other stations, the Love wave data seemed to indicate the presence

of two crustal layers of slightly different velocity. This assumption could not be checked by the Rayleigh wave dispersion since no usable theory has been developed for this in the two-layer case.

There is some question whether the distinctions arbitrarily set up between the dispersion curves observed at the two groups of stations are sufficient to justify the conclusion that the structure of the crust between the two seas is different. Dispersion data are highly ambiguous to interpret and caution is advisable in their use. Nevertheless, the paper represents an important contribution to seismology, and it is hoped that earthquakes in other parts of the world will give records from which the dispersion of both types of waves can be analyzed.

MILTON B. DOBRIN

PUBLICATIONS RECEIVED

American Journal of Science, Vol. 250, No. 12 (Dec., 1952); Vol. 251, Nos. 1, 2 & 3 (Jan. Feb. & Mar., 1953)

Annales de Geophysique, Vol. 8, No. 3 (July-Sept., 1952)

Annali di Geofisica, Vol. 5, Nos. 2 & 3 (April & July, 1952)

Boletin de la Asociacion Mexicana de Geologos Petroleros, Vol. 4, Nos. 5–6 & 7–8 (May–June & July–August, 1952)

Bulletin of the Seismological Society of America, Vol. 42, No. 4 (October, 1952)

Economic Geology, Vol. 47, Nos. 7 & 8 (Nov. & Dec., 1952); Vol. 48, No. 1 (Jan.–Feb., 1953)

Erdol und Kohle, Vol. 5, Nos. 10, 11 & 12 (Oct., Nov., & Dec., 1952); Vol. 6, No. 1 (Jan., 1953)

Institute of Petroleum Review, Vol. 7, No. 73 January, 1953)

Journal of Geophysical Research, Vol. 57, No. 4 (Dec., 1952)

Journal of the Institute of Petroleum, Vol. 38, No. 348 (Dec., 1952)

Proceedings of the Cambridge Philosophical Society, Vol. 49, No. 1 (Jan., 1953)

Quarterly Journal of the Geological Society of London, Vol. 107, Part 4 (Nov., 20, 1952); Vol. 108, Part 1 (December 29, 1952)

Revista de Geofisica, Vol. 11, Nos. 41 & 42 (Jan.–Mar. & April–June, 1952)

Revista de Geofisica Applicata, Vol. 13, No. 1 (1952)

Science, Vol. 116, Nos. 3021 through 3026 (Nov. 21 weekly through December 26, 1952); Vol. 117, Nos. 3027 through 3036 (Jan. 2 weekly through March 6, 1953)

Science Reports of the Tohoku University, 5th Series, Geophysics, Vol. 4, No. 2 (Oct., 1952)

Scientific Monthly, Vol. 75, Nos. 5 & 6 (Nov. & Dec., 1952); Vol. 76, Nos. 1 & 2 (Jan. & Feb., 1953)

Tellus, Vol. 4, No. 3 (August, 1952)

DISCUSSIONS AND COMMUNICATIONS

LETTER TO THE EDITOR

Mr. Paul L. Lyons, Editor, *Geophysics*
The Carter Oil Company
Box 801
Tulsa 2, Oklahoma

Dear Sir:

During the past three years, work at the Massachusetts Institute of Technology on the application of linear operators to the analysis of seismic records has indicated the possibility that some information may be derived from these records that has not been obtainable heretofore, and that the analysis also provides further insight into the nature of seismic responses and the dynamical properties of the earth. A Geophysical Analysis Research Project has now been instituted to carry on and increase the small program which formerly was supported by the Massachusetts Institute of Technology.

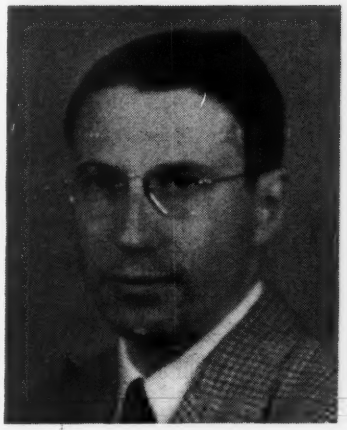
The project is being supported by individual grants-in-aid from oil companies and geophysical service companies who are interested in advancing this type of research. In recognition of the possibility that other companies may desire to participate, we are giving notice to the effect that full participation in the project is open at any time to all interested companies. Further information may be obtained by contacting P. M. Hurley, Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge 39, Mass.

We should appreciate it if you would publish this letter in *Geophysics* under Discussions and Communications.

Very truly yours,
PATRICK M. HURLEY,
Associate Professor of Geology and Geophysics
Massachusetts Institute of Technology

Cambridge Mass.
March 4, 1953

CONTRIBUTORS



ROBERT B. BAUM

ROBERT B. BAUM received the B.S. degree in geology from the University of Chicago in 1941. He has been engaged in geophysical exploration with Seismograph Service Corp. since 1941, serving as party chief, supervisor, and district manager, in offshore Canada, offshore East Coast, Midcontinent, Illinois-Indiana, West Texas, and Gulf Coast.

Mr. Baum is married and has three children. He is a member of The American Association of Petroleum Geologists, American Association for the Advancement of Science Shreveport Geologiacl Society, Ark-La-Tex Geophysical Society, Mississippi Geological Society, and Society of Exploration Geophysicists.

RICHARD BREWER

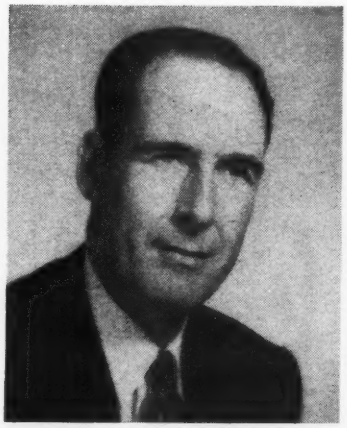
RICHARD BREWER received his B.S. degree in Electrical Engineering from Purdue University in 1935. After one semester of graduate work, he joined the Shell Petroleum Corporation as Assistant Seismologist in January, 1936. In early 1942, he was commissioned a lieutenant in the Army Signal Corps and served with that group for 4½ years. In 1946 he resigned from the Shell Oil Company to join the Atlantic Refining Company.

Mr. Brewer is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, the Ark-La-Tex Geophysical Society, and Sigma Pi Sigma.

KARL DYK

KARL DYK received his B.A. degree in physics in 1929 and his PhD in seismology in 1934, both from the University of California. During the years following his graduation in 1929, and while studying for his doctorate, he worked with the U.S. Coast and Geodetic Survey, doing research in submarine acoustics. He continued with the Survey until 1935, when he joined Stanolind Oil and Gas Company as a computer on a seismograph party. His present position is Chief Geophysicist for Stanolind Oil and Gas Company.

Dr. Dyk is a member of a number of professional and scientific societies, and has been a member of the Society of Exploration Geophysicists since 1938.



W. RAYMOND GRIFFIN

W. RAYMOND GRIFFIN graduated from Baylor University in 1936 with an A.B. Degree in Physics. Following a two year fellowship in mathematics at Texas Agricultural and Mechanical College, he received the M.S. Degree in that subject. He then taught mathematics in the high schools of the state for two years.

In 1940 he became associated with Curtiss-Wright at St. Louis, Missouri, as a stress analysist. After a half year, he was transferred to the Flutter and Vibration Group as a vibration Engineer. He served in that capacity until July, 1945.

In the following month, he became affiliated with Robert H. Ray Company of Houston as their Research Geophysicist. While there, he was responsible for the research and development of quantitative methods of residual gravity analysis.

After six months as a statistician for a major railroad, he became associated with Chance Vought Aircraft Corp. of Dallas in January, 1951 as a Senior Analytical Engineer. At present he is in charge of publicity there for The Texas Section of the Institute of Aeronautical Sciences.

Mr. Griffin is a member of the Society of Exploration Geophysicists, the Dallas Geophysical Society, the Texas Academy of Science, and the Institute of Aeronautical Sciences. He is listed in *Who's Who* in the South and Southwest.

J. B. H. HENDERSON received his B.S. Degree from Rice Institute in 1927. Upon graduation he was employed in various phases of the oil industry until 1934 when he formed the Hegralle Oil Company and the Oleander Petroleum Company. These were liquidated in 1940 and at that time he formed Survey Drilling Company in partnership with Fred Lehmann which has engaged in the drilling of structure and stratigraphic holes in the United States and Canada with the operation of logging and other informational services in conjunction.

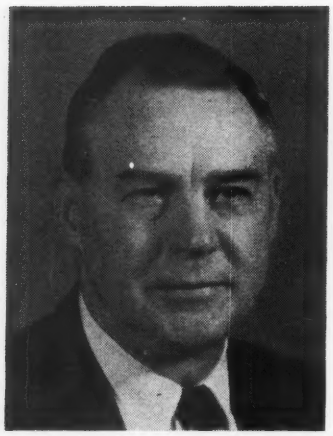
J. B. H. HENDERSON

HYMAN KAUFMAN

HYMAN KAUFMAN received the B.Sc. degree in mathematics and physics in 1941, M.Sc. in physics in 1945, and Ph.D. in physics in 1948, at McGill University. He did additional graduate study in applied mathematics at Brown University during 1945–46, and in electrical engineering at Yale University during 1948–49.

He was employed by Continental Oil Company as research geophysicist from 1949 to 1951, and by Laboratory for Electronics, Inc., as physicist from 1951 to 1952, and was appointed to an associate professorship in mathematics at McGill University in September 1952.

Dr. Kaufman is an associate member of Society of Exploration Geophysicists and of Institute of Radio Engineers, and a member of American Geophysical Union, Mathematical Association of America, Canadian Mathematical Congress, American Association for the Advancement of Science, and Sigma Xi.



OTIS W. SWAINSON

OTIS W. SWAINSON received his E.M. degree from the Colorado School of Mines in 1910. He received an appointment in the engineering field service of the United States Coast and Geodetic Survey and remained in that Bureau until his retirement in 1949. He commanded hydrographic survey vessels in Atlantic and Pacific coastal waters and the seas around the Philippine Islands, taking an active part in developing techniques in echo sounding and radio acoustic ranging. He spent a year in charge of the Northwestern District, U.S.C. and G.S., and three years in charge of the Western District. From 1938 to 1941 he was Assistant Chief of the Division of Geomagnetism and Seismology and was Chief of that Division from 1941 to 1945.

Captain Swainson is a member of numerous engineering and scientific societies, and is a Past President of the Eastern Section of the Seismological Society of America.

STANLEY H. WARD was born in Vancouver, Canada, in 1923. He attended the course in Engineering Physics, Geophysics Option, at the University of Toronto, graduating with the B.A.Sc. degree in 1949. During the following three years he undertook post-graduate studies in the Geophysical Laboratory of the Department of Physics at the University of Toronto, receiving his M.A. in 1950 and his Ph.D. in 1952. He has been associated with McPhar Geophysics Limited since its inception in 1950 and has been general manager of that firm since early 1951.

Dr. Ward is a member of the Association of Professional Engineers of the Province of Ontario, the Society of Exploration Geophysicists, the American Geophysical Union, and the Canadian Association of Physicists.

STANLEY H. WARD

ŽELJKO ZAGORAC

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The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days.

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ANNOUNCEMENTS

GEOLOGISTS MEET AT MIDWEST INTER-LIBRARY CENTER

An all-day meeting of geologists, representing 13 midwestern university geology departments, was held on February 28, 1953 at the Midwest Inter-Library Center in Chicago. The meeting was called by the Center to explore possibilities for the cooperative acquisition of less-used but important library materials in the field. As an outgrowth of the discussions, the geologists decided that the universities that participate in the Midwest Center might appropriately supplement their own collections with a comprehensive collection of foreign geologic maps and with files of minor and less-used journals, particularly those of foreign academies. Such materials would be acquired by and housed at the Center for the joint use of the several institutions.

The Center purchases less-used research books and periodicals that its individual member libraries cannot afford and extends the use of them freely within the group of participants. It was established in 1949 with a million-dollar foundation grant and is supported and controlled by 16 member universities. Its new library building in Chicago has a three-million-volume capacity bookstacks and is connected with each member library by teletype.

The participants at the February 28 meeting in Chicago were:

Eugene N. Cameron (University of Wisconsin)
Leland Horberg (University of Chicago)
Arthur L. Howland (Northwestern University)
Brian H. Mason (Indiana University)
Archie J. MacAlpin (University of Notre Dame)
R. C. Moore (University of Kansas)
Willard H. Parsons (Wayne University)
John L. Rich (University of Cincinnati)
Charles H. Summerson (Ohio State Univ.)
George A. Thiel (University of Minnesota)
James W. Trow (Michigan State College)
Sherwood D. Tuttle (State Univ. of Iowa)
George W. White (University of Illinois)

Library Consultants were:

Lyle E. Bamber (Natural History Librarian, University of Illinois)
Leon Marshak (Research Staff, John Crerar Library)
George R. Meluch (Purdue University Library)
Mrs. Marie K. Shaw (Science Librarian, Wayne University)

PERSONAL ITEMS

LESLIE C. SPENCER and JESSE E. SPENCER have formed a partnership entitled Mountain Geophysical Company, with offices at 325 Denham Bldg., Denver 2, Colorado.

WILLIAM P. OGILVIE has resigned from The California Standard Co. and has accepted a position with Accurate Geophysical Ltd., 1023 11th Avenue West, Calgary, Alberta, Canada.

HAMILTON M. JOHNSON, Instructor in Engineering Geology, The University of Oklahoma, Norman, Oklahoma, advises that he would like to hear from anyone who may be willing to sell the following issues of *Geophysics:* Vol. 3, Nos. 1, 3, & 4; Vol. 6, No. 1; Vol. 7, No. 1; Vol. 8, No. 2; Vol. 9, No. 1; and Vol. 10, Nos. 1 & 2.

The promotion of PAUL C. COOK to the position of Seismic Supervisor of Keystone Exploration Company, Houston, Texas has been announced by C. C. ZIMMERMAN, manager.

Mr. Cook, a graduate of the United States Naval Academy, entered the seismic exploration field in 1937 as computer for The Texas Company. During World War II, he was on active duty with the Navy and was released with the rank of Lieutenant Commander. He joined Keystone Exploration Company in 1945 as seismic party chief. He has seen service in the Appalachian area, California, the Gulf Coastal areas, the Illinois Basin, and in Egypt. In his new assignment, Mr. Cook will supervise Keystone's crews in the Rocky Mountain area and California.

L. C. FOOTE party chief with Geophysical Service Inc., on the West Coast, is now located in Salvador, Bahia, Brazil.

J. E. ARCENEAU is now a party chief with Geophysical Service Incorporated at Belem, Para, Brazil.

E. J. EVERITT, seismologist with Geophysical Service Inc., is serving as a consultant to the Institut Francais du Petrole in Paris, France.

GORDON D. CLOEPFIL has been promoted to supervisor of Geophysical Service Inc., in its Rocky Mountain division, with headquarters at 624 18th Street Northwest, Minot, North Dakota.

PAUL E. SWENSON has received a promotion from party chief to supervisor of Geophysical Service Inc., and is operating out of the Bakersfield, California, office.

A. H. SMITH, JR., and LEWIS RAMSEY, seismologists with Geophysical Service Incorporated, are located in Maracaibo, Venezuela.

L. A. SCHOLL JR., who had a 36-year career in domestic and foreign operations of The Texas Company, will retire December 31 as geophysical consultant on the general manager's staff, The Texas Company, Producing Department, it was announced by E. R. Filley, general manager of the Producing Department.

Mr. Scholl was born in Pittsburgh, Pa., and was graduated from Carnegie Institute of Technology with the B.S. degree in mining engineering. He also received the E. M. degree from the School of Mines, Columbia University, in 1916, and started that year with the old Producers Oil Company, a Texaco subsidiary, as a geologist.

He was promoted to division geologist at Tulsa in 1918. Mr. Scholl was made chief geologist, Houston, in 1920 and soon afterward was transferred to Venezuela, where he remained until July, 1925.

Following a year of graduate study at the University of California, he became consulting geologist, New York. In 1929, he was made chief of the Geophysical Division, Houston.

He was appointed manager of the division on September 1, 1945, and was named geophysical consultant on the general manager's staff on April 1, 1950.

Mr. and Mrs. Scholl live at 5040 Cedar Creek, Houston.

Geophysical Service Inc., is offering its personnel correspondence work covering the entire field of seismic exploration. Begun in October, 1952, on a strictly voluntary basis, the study program already has an enrollment of 30 students from GSI crews operating in the United States. From foreign operations, an additional 30 students with Geophysical Service International Corporation, Geophysical Service International S.A., and Geophysical Service Incorporated bring the total enrollment to 60.

Personnel enrolled are party chiefs, seismologists, and computers. The courses offered cover all phases of seismic exploration work, from surveying and chart construction to geology and interpretation of seismograms.

ROY FULLER, GSI correspondence training director, is in charge of the program under supervision of E. J. STULKEN, chief seismologist for GSI.

GLENN M. MCGUCKIN, formerly seismologist and supervisor for Magnolia Petroleum Co., and for the past 7 years organizer and partner in Reliable Geophysical Co., has sold his interest in Reliable with the purpose of following a less strenuous life as a seismograph consultant. For the time being he will remain at Yoakum, Texas.

HERBERT HOOVER, JR., announces that effective January 1, 1953, Mr. C. C. LISTER became president of United Geophysical Company. Mr. Hoover continues as chairman of the board of directors and maintains his offices with the company in Pasadena.

After graduating from Texas Tech and serving in the Geophysical department of Mid-Continent Petroleum Corporation at Tulsa, Mr. Lister joined United Geophysical Company in 1937. The first 10 years of his connection with the Company were spent in foreign service. He was a member of

United's first party to Trinidad and subsequently worked in Brazil and Colombia. After serving as Manager in Venezuela he moved to the Pasadena office and became Manager of United's Foreign Operations. More recently, he has been Vice President in Charge of Operations.

R. G. SOHLBERG, recently Manager of Canadian operations, has moved to the Pasadena headquarters of the company as vice president of operations.

S. O. PATTERSON, who was formerly assistant manager in Canada, succeeds Mr. Sohlberg as Canadian manager.

Mr. L. A. MARTIN was recently elected Vice President and Chief Geophysicist of United Geophysical Company. He has been with United since 1946 and has served as Manager in Venezuela and Manager of Foreign Operations.

Mr. Martin graduated from the University of California in 1934 in geophysics and later received an M.A. degree from California Institute of Technology. He was with the Shell organization for six years after graduating, much of which time was spent on foreign assignments.

The promotion of R. L. WALES to assistant division manager of the Oklahoma Division of the Producing Department, The Texas Company, effective April 1, was announced by J. N. TROXELL, general manager of Texaco's Producing Department, and M. L. TERRY, division manager of the Oklahoma Division.

Now assistant to manager of the Geophysical Division, in charge of geophysical operations in Canada, Wales has been located in Calgary, Alberta, Canada, and in his new assignment will have headquarters in Tulsa, Oklahoma. He will replace Harvey Cash who has been transferred to the Company's Foreign Operations Department in New York.

Wales is a native of Saskatchewan, Canada, and a graduate of the University of Saskatchewan (1934), with a B.S. Degree in Chemical Engineering. He entered the service of the Texas Company as assistant recorder in the Geophysical Division on May 1, 1936, with headquarters in the South Texas area.

He was made computer on January 1, 1937, and seismic party chief, August 1, 1940. He served as party chief in the mid-continent and Rocky Mountain areas until September 1, 1947, when he was moved to Canada. On April 1, 1948, he was made supervisor of geophysical field operations in Canada, and was promoted to his present position on November 1, 1951.

WALTER R. FILLIPPONE has been appointed Area Manager for United's operations in the Rocky Mountains and Williston Basin Area and FLINT H. AGREE as Area Manager of United's West Coast Area as announced by C. C. LISTER, President of United Geophysical Company of Pasadena, California. Fillippone received his M.S. degree from the California Institute of Technology in 1944 and has been continuously associated with United since 1943. Although recently in charge of United's Alaskan operations, most of his career has been closely linked with the Rocky Mountain exploration problems. His headquarters, will be in United's new office which is located in the McClintock Building, 1554 California Street, Denver, Colorado. Agree has been associated with United as party chief and supervisor of California seismic and water parties since 1945. He received his degree in geology from U.C.L.A. in 1933 and worked for Western and National before coming with United. He will continue to maintain his headquarters at United's offices in Pasadena, California.

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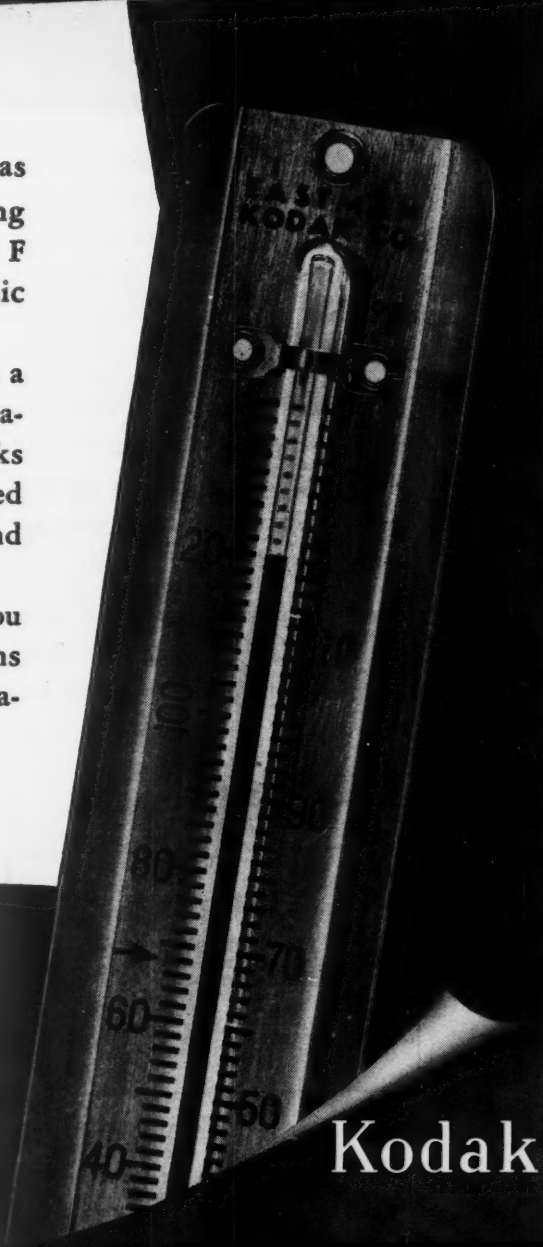

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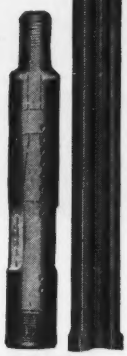

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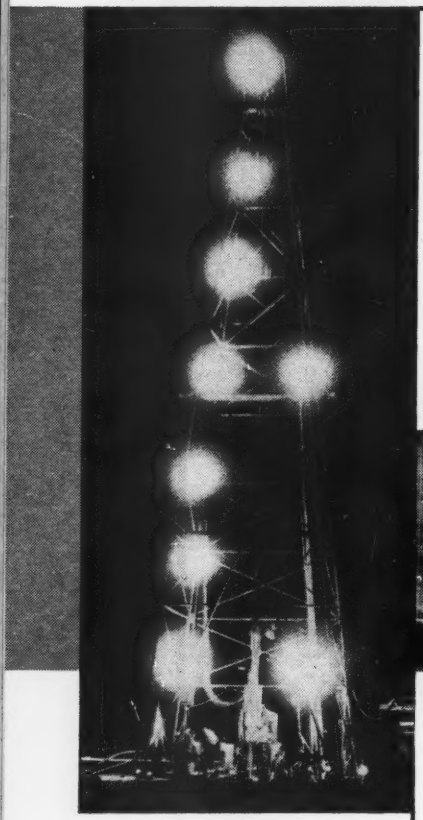

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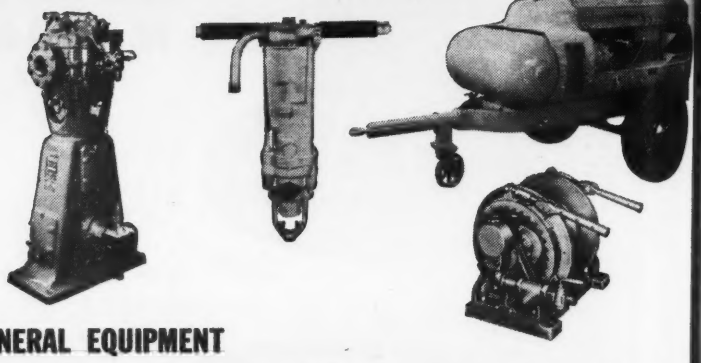

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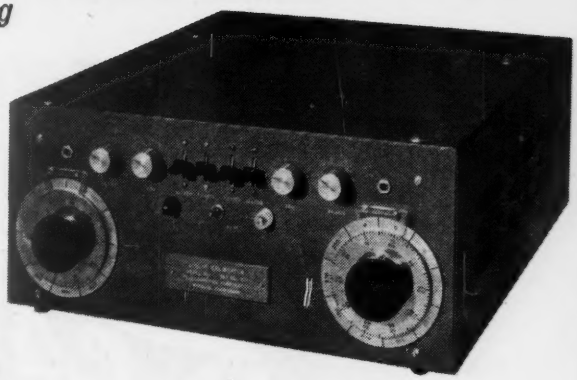

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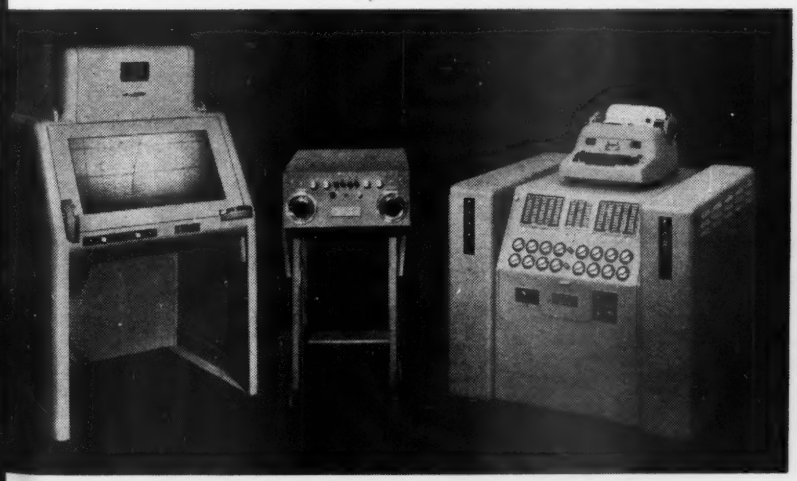

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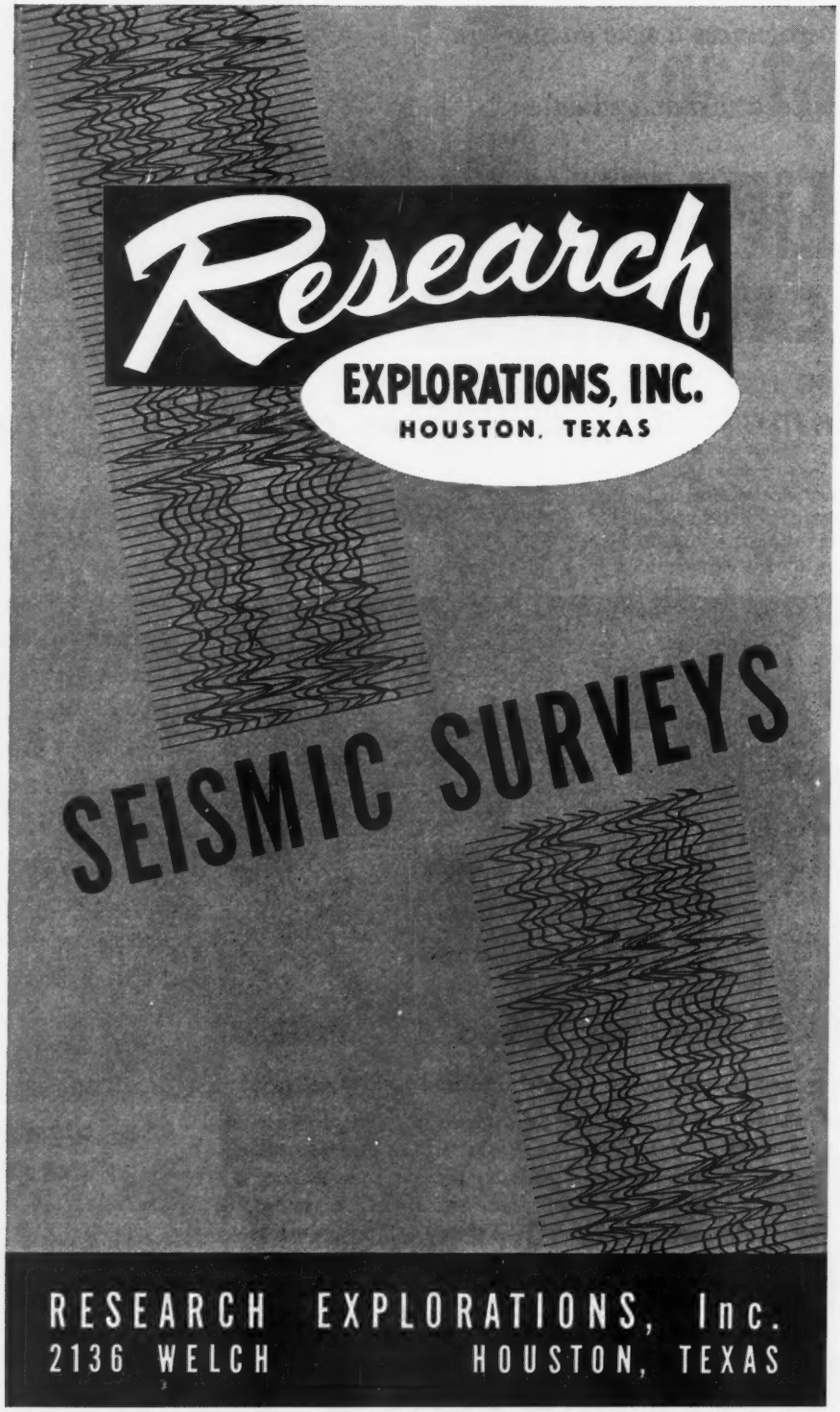
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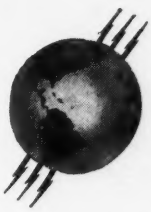

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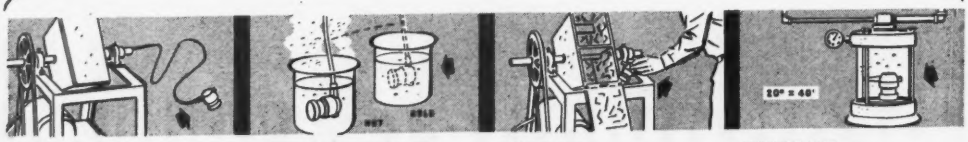
Another result . . . another reason why General's planned program of equipment improvement helps insure success in deeper exploration. General's new seismometer design was completed after several years of scientific research. Its hard chrome-plated steel case houses improved springs, coils, coil leads and numerous other exclusive features that combine to insure constant maximum performance. A new plug-in type connection is hermetically sealed in as a safeguard against moisture seepage. Before this modern instrument was put into service by General's experienced crews, it was subjected to extreme tests of durability and exacting performance under the most adverse field conditions. TODAY, GENERAL IS BETTER EQUIPPED TO SERVE YOU THAN DURING ANY OF ITS DECADE OF DEPENDABLE SERVICE.

NEW PLUG-IN TYPE PIG TAIL

Designed to form a snug, trouble-free connection and eliminate time consuming field maintenance. Its sockets fit onto durable beryllium copper base-plugs made exclusively for General. This new feature is the only successful development of its kind now in use.

4 RIGID TESTS



SNAKE KILLER TEST: Pig tail end is attached to mechanical whipping arm. Rapid jolts test durability of the unit and its connection.

HOT AND COLD WATER TEST: To test moisture resistance, unit is submerged in boiling salt water then in iced salt water.

TUMBLER TEST: Unit is in perfect condition after 20 hours of severe pounding against sides of iron case.

PRESSURE TEST: In water filled pressure chamber, unit remains under 20 lb. pressure for 7-day period.

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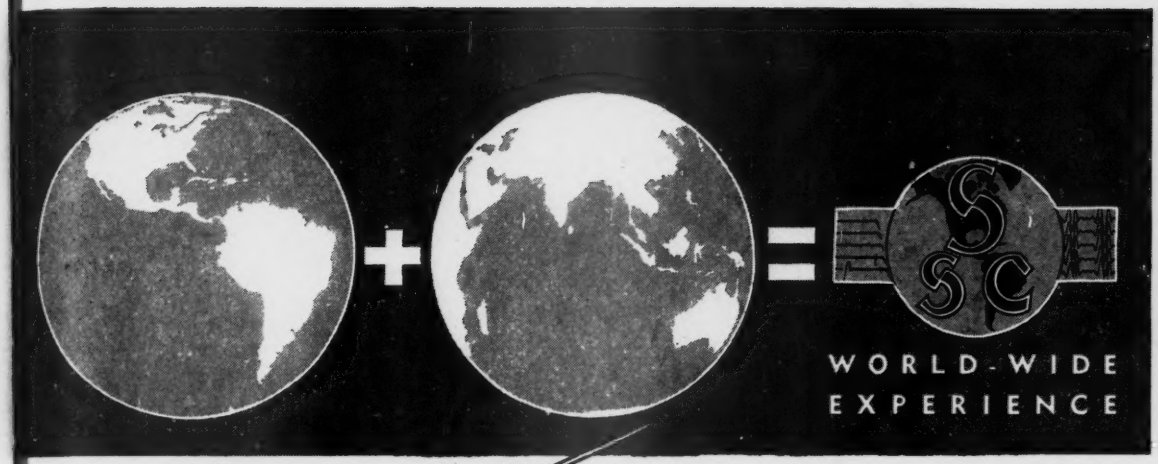

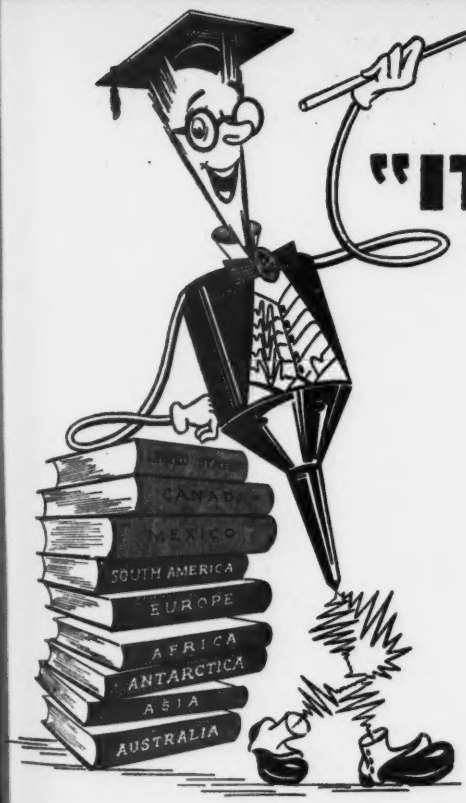

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